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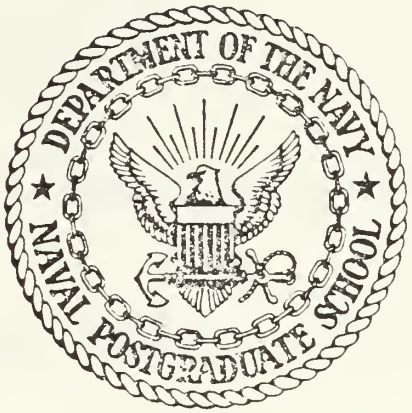

THESIS

RADAR TARGET IDENTIFICATION THROUGH
ELECTROMAGNETIC SCATTERING STUDIES

by

Mario Lolic

December 1984

Thesis advisor: Hung-Mou Lee

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the radar cross section and the phase of the return on several finite length, thin walled, right circular cylinders were done.

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Radar Target Identification through Electromagnetic Scattering Studies

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

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December 1984

ABSTRACT

Radar target identification using electromagnetic scattering in the Mie or resonant region is discussed. Frequencies being used are those corresponding to wavelengths from half the target size to one-tenth the target dimensions. The frequency domain calibration of the free field radar range at the Naval Postgraduate School is performed and validated on several perfectly conducting metallic spheres. Measurements of the radar cross section and the phase of the return on several finite length, thin walled, right circular cylinders were done.

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I. INTRODUCTION

A. TARGET IDENTIFICATION

In most radar applications so far, the only properties of the target that are measured are its location in range and angle. Such radars are sometimes called blob detectors since they recognize targets only as "blobs" located somewhere in the space. In the era of modern electronic warfare it is desirable, however, to extract more information about the target. Radar should be able to recognize one type of target from another; that is,to determine that the target is a Boeing 747 aircraft and not a DC-10, or that the particular ship is a warship and not a freighter. This capability is called target identification or classification.

Generally, radar target identification requires a larger signal to noise ratio then normally needed for detection. Hence, it is to be expected that the range at which target identification can be made would be less than the range at which the target can be first detected.

One of the approaches that might be used for target identification is that of electromagnetic back scattering.

The frequencies that are suggested as being important are those corresponding to wavelengths from half the target size to wavelengths about one-tenth the target dimensions The use of such frequencies is said to provide overall dimensions, approximate shape, and material composition of the target [Ref. 1].

It is particularly useful to investigate the resonances excited by electromagnetic fields of different frequencies incident on the target. At resonant frequencies the scattered fields are stronger compared to non-resonant

situation. The back scattering cross sections are larger and provide easier target detection and identification.

Associated with resonant frequencies are the natural modes. A natural mode is defined as a possible "source-free" distribution of surface current on the scatterer according to Stratton [Ref. 6]. When the target is irradiated with an incident electromagnetic wave, surface current is excited on it. This surface current radiates and generates the scattered field. A resonance occurs when one or certain combination of the natural modes responds very strongly to a particular type of excitation. The natural modes are defined only by the geometrical structure and the composition of the target, hence the resonant frequencies will be only functions of the target's physical configuration. Note that the resonant frequencies refered to in this thesis are real constants, in contrast to the "natural resonance" frequencies of the Singularity Expansion Method [Ref. 2].

Investigation of target back scattering over a broad frequency band appears to be a promising method to achieve target identification. If the phase shift as well as the amplitude of the scattered field are measured, fewer frequencies might be utilized than when amplitude alone is obtained [Ref. 3].

The polarization of the radar back scattered energy depends on the target properties and differs, in general, with the polarization of the energy incident on the target. This property can be used as a possible basis for discriminating one target from another [Ref. 4]. For example, a thin straight wire can be readily distinguished from a homogeneous sphere by observing the variation of the back scattered field amplitude as the polarization is rotated. The field amplitude from the sphere will be unmodulated, and the back scattered field amplitude from the wire will vary

between a maximum and minimum at twice the rate at which the polarization is rotated. By transmitting two orthogonal polarizations and measuring the amplitude and phase of the received back scattered field on each polarization, as well as the cross-polarization component, additional means of target identification can be provided. It is worthwhile to indicate that non-cooperative target recognition through various methods has been an ongoing topic of intensive research for at least two decades.

B. THESIS OBJECTIVES

This work should serve as the basis of what is a long term ongoing project at the Naval Postgraduate School. It is the theoretical and experimental studies of the scattering characteristics of targets and the development of radar target identification schemes.

The main goal of this work is to calibrate the continuous wave (CW) scattering range. This is the first step toward studing target scattering characteristics for target identification. Calibration has been performed by using an assortment of perfectly conducting metallic spheres of known cross sections. The theoretical solution has been tested against experimental results for the spheres of different diameters and two orthogonal polarizations, horizontal and vertical. After calibration, the next step was a series of measurements on the right circular cylinders having very thin walls and finite lengths made of brass and stainless steel. They come in three diameters and several different length to diameter ratios. Measurements of magnitudes and phases of back scattering fields from the tubular cylinders were carried out and corresponding back scattering cross sections are obtained. Those results should serve as the basis for future works in the ongoing project. A right

circular cylinder is chosen because of its resemblance to a missile body. Progressively more complicated models evolving from a tubular cylinder to a missile will be constructed and studied. Each model which represents a step forward in increased complexity from a simpler one will be considered as a perturbation to the physical structure of the simpler model. By comparing the scattering data of the models to those of tubular cylinders, the effects of the successive perturbations to the physical structure on the back scattering cross section and phase shift can be observed. Explanations of these effects is currently being attempted. Application of this technique toward target identification and radar cross section reduction will be explored.

In chapter II the general approach to the solution of the problem of electromagnetic scattering is given. In particular, the exact solution for the scattering by a perfectly conducting sphere is presented along with the considerations on the back scattering cross section.

Chapter III describes experimental setup in the scattering laboratory of the Naval Postgraduate School and the measurement procedure, as well as the validation of measurement data.

Computer programs for the evaluation of the data for a sphere, system calibration and target data acquisition are described in the chapter IV.

Chapter V contains a summary and conclusions. It also discusses results and problems encountered during this work.

II. ELECTROMAGNETIC SCATTERING PROBLEMS AND SOLUTIONS

A. GENERAL APPROACH TO THE PROBLEM

A typical problem in electromagnetic scattering involves three principal elements; these are:

1. A transmitting system consisting of an antenna or radiator that is excited by a generator of an electromagnetic disturbance of known behavior in time;

2. An obstacle of arbitrary shape, size, orientation, and material that is fixed or is moving in any direction and manner at an unrestricted distance from the source;

3. Receiving antenna with associated apparatus for determining amplitude, phase, and the polarization of the electromagnetic field at any point in space, including the surface (or surfaces) of the obstacle.

The oscillating charges and currents in the driving or primary antenna constitute the source. The electromagnetic field maintainedby them is the primary or incident field. It is denoted by a superscript "i": thus, $\vec{E}^{i}$, $\vec{H}^{i}$. The parasitic element under study is known as obstacle, radiator, scatterer or target, depending partially on its shape and function. The current in the source induces time-varying distributions of oscillating charges and currents in the scatterer. These, in turn, maintain an electromagnetic field that is known as a scattered, or reradiated field. It is denoted by a superscript "s": thus, $\vec{E}^{s}$, $\vec{H}^{s}$. The total field $\vec{E}^{T}$, $\vec{H}^{T}$, is the vector sum of the incident and the scattered fields. It is a resultant field at any point when the obstacle is present and the source is active. Thus, $\vec{E}^{T} = \vec{E}^{i} + \vec{E}^{s}$, $\vec{H}^{T} = \vec{H}^{i} + \vec{H}^{s}$, Figure 2.1.

In general, the incident field is not independent of the scattered field in the sense that the currents and the charges in the source are not the same when the obstacle is present as when it is removed to infinity. The incident field does depend upon the presence and nature of the

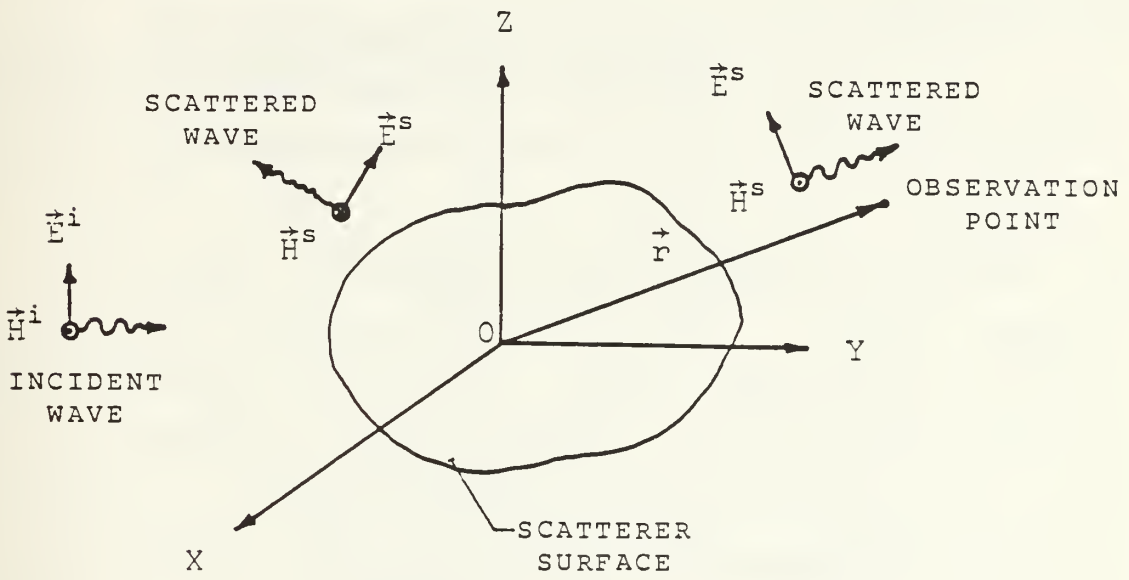

Figure 2.1 Configuration of a Scattering Problem

obstacle, at an arbitrary point in space. In order to simplify the theoretical problem, it is usually assumed that the source is so loosely coupled to the obstacle, usually by a sufficiently large separation, that the currents and charges in the source may be regarded as independent of those in the obstacle. In this case, the incident field at any point may be treated as a quantity that is independent of the scattered field; it may, therefore, be determined in the absence of the obstacle. Alternatively, the scattered field may be obtained by subtracting the incident field in the absence of the obstacle from the total field at the same point when the obstacle is present.

The fundamental problem in scattering is the determination of the scattered field amplitude, phase and polarization. The scattering of EM wave from an obstacle is a boundary value problem. It is often hard, if not impossible,to obtain the exact solution, unless the shape of the obstacle coincides with one, of the limited, simple coordinate systems.

To solve the problem, it is necessary, as usual, to start from Maxwell equations. The first step is to determine the scattered EM field in the surrounding space due to the currents on the surface of the scatterer. The boundary conditions on the surface are then applied to obtain a set of coupled equations, containing all components of the surface current. Only recently has become practical with the use of high-speed digital computers to estimate surface currents flowing on the body by a finite-difference solution to a network of simultaneous equations [Ref. 5]. Because of the limitations of computation time and storage capability, the finite-difference solution is applicable only when the dimensions of the target do not exceed a few wavelengths. For almost all practical problems, the use of approximate methods is the only practicable approach.

With surface current distribution determined, other quantities such as the far field pattern and the scattering cross section are obtained from the scattered field evaluated at the begining.

B. SCATTERING BY A SPHERE

A sphere is the simplest object susceptible to exact solution by the method of separation of variables. The literature on electromagnetic scattering by spheres is extensive, and a great deal is now known in detail concerning the surface current distribution and the

scattered field in the neighborhood of the sphere [Ref. 6]. The exact solution of the scattering of a plane EM wave by an isotropic, homogeneous sphere was obtained by Mie in 1908 and is usually refered as the Mie solution.

1. Exact Solution

The geometry of the problem in spherical coordinates r, θ, ϕ is depicted in the Figure 2.2.

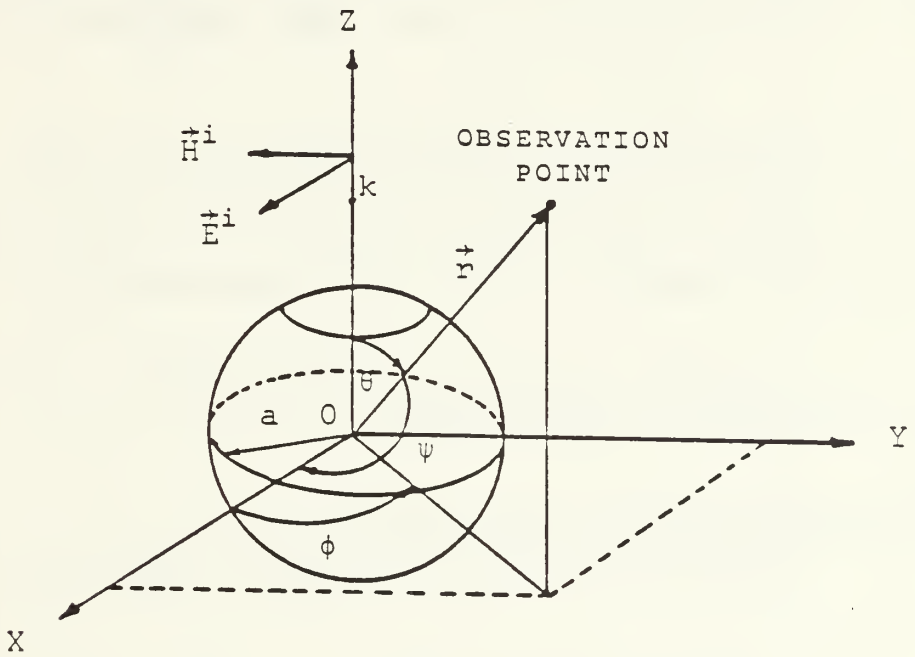

Figure 2.2 Geometry of Scattering by Sphere

Let us consider a sphere with a relative dielectric constant ε_r and an incident wave propagating in the z-direction and polarized in x-direction.

$$\vec{E}^i = E_0 e^{ikz}\hat{x} \qquad (2.1)$$

In the spherical coordinate system it is possible to express any electromagnetic field in terms of two scalar functions (Hertz potentials) which are the radial components of the electric and magnetic Hertz vectors [Ref. 7],

$$\vec{\Pi}_e = \Pi_1 \cdot \hat{r} \qquad \text{and} \qquad \vec{\Pi}_m = \Pi_2 \cdot \hat{r} \tag{2.2}$$

Both Π_1 and Π_2 satisfy a scalar wave equation

$$(\nabla^2 + k_2^2) \cdot \Pi = 0 \qquad \text{for} \quad r > a \tag{2.3}$$

Electric and magnetic field can be expressed as

$$\vec{E} = \nabla\times\nabla\times(r\Pi_1\hat{r}) + i\omega\mu_0\nabla\times(r\Pi_2\hat{r})$$

$$\vec{H} = -i\omega\varepsilon\nabla\times(r\Pi_1\hat{r}) + \nabla\times\nabla\times(r\Pi_2\hat{r}) \tag{2.4}$$

It can be shown that the general solution of the scalar wave equation in spherical coordinates may be obtained by a linear superposition of the particular solutions, thus

$$r\Pi = r \cdot \sum_{n=0}^{\infty} \sum_{m=-n}^{n} \Pi_n^{(m)} \tag{2.5}$$

$$= \sum_{n=o}^{\infty} \sum_{m=-n}^{n} \{c_n \Psi_n(kr) + d_n \chi_n(kr)\}\{P_n^{(m)}(\cos\Theta)\}$$

$$\{a_m \cos(m\Phi) + b_m \sin(m\Phi)\}$$

The isotropic, homogeneous medium will be considered to be a dielectric so that the propagation constant k_2 is real, and the isotropic homogeneous sphere is characterized by a propagation constant k_1 which may not be complex. The ratio of these quantities defines the relative refractive index.

$$m = \frac{k_1}{k_2} = \frac{m_1 k_0}{m_2 k_0} = \frac{m_1}{m_2} \tag{2.6}$$

The incident field, given in the equation (2.1) can be derived from the two scalar functions Π_1^i and Π_2^i and are expressed in the following spherical harmonic functions:

$$r\Pi_1^i = \frac{1}{k_2^2} \sum_{n=1}^{\infty} \frac{i^{n-1}(2n+1)}{n(n+1)} \Psi_n(k_2 r) P_n^1(\cos\theta)\cos\phi$$

$$r\Pi_2^i = \frac{1}{k_2^2} \sum_{n=1}^{\infty} \frac{i^{n-1}(2n+1)}{n(n+1)} \Psi_n(k_2 r) P_n^1(\cos\theta)\sin\phi \tag{2.7}$$

In the same way, we write general expression for the scattered fields for r>a using arbitrary constants a_n and b_n :

$$r\Pi_1^s = -\frac{1}{k_2^2} \sum_{n=1}^{\infty} \frac{i^{n-1}(2n+1)}{n(n+1)} a_n \zeta_n(k_2 r) P_n^1(\cos\theta)\cos\phi$$

$$r\Pi_2^s = -\frac{1}{k_2^2} \sum_{n=1}^{\infty} \frac{i^{n-1}(2n+1)}{n(n+1)} b_n \zeta_n(k_2 r) P_n^1(\cos\theta)\sin\phi \tag{2.8}$$

It can be shown that by applying boundary conditions we can get four linear equations in the coefficients a_n, b_n, c_n, and d_n. These equations can be solved for that sets of coefficients. Only first two are of interest here, and these are given by

$$a_n = \frac{\Psi_n(\alpha)\cdot\Psi_n'(\beta) - m\Psi_n(\beta)\cdot\Psi_n'(\alpha)}{\zeta_n(\alpha)\cdot\Psi_n'(\beta) - m\Psi_n(\beta)\cdot\zeta_n'(\alpha)} \tag{2.9}$$

$$b_n = \frac{m\Psi_n(\alpha)\,\Psi_n'(\beta) - \Psi_n(\beta)\Psi_n'(\alpha)}{m\zeta_n(\alpha)\,\Psi_n'(\beta) - \Psi_n(\beta)\zeta_n'(\alpha)}$$

where

$$\alpha = k_2 a = 2\pi a/\lambda = 2\pi m_2 a/\lambda_0$$

$$\beta = k_1 a = 2\pi m_1 a/\lambda_0 = m\alpha$$

The scattered fields E_Θ and E_Φ far from the sphere are given by

$$E_\Phi = -\frac{E_0 i e^{ik_2 r}}{k_2 r} S_1(\Theta)\sin\Phi \tag{2.10}$$

$$E_\Theta = \frac{E_0 i e^{ik_2 r}}{k_2 r} S_2(\Theta)\cos\Phi$$

where

$$S_1(\theta) = \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} \{a_n \pi_n(\cos\theta) + b_n \tau_n(\cos\theta)\} \tag{2.11}$$

$$S_2(\theta) = \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} \{a_n \tau_n(\cos\theta) + b_n \pi_n(\cos\theta)\}$$

$$\pi_n(\cos\theta) = \frac{P_n^1(\cos\theta)}{\sin\theta}, \qquad \tau_n(\cos\theta) = \frac{d}{d\theta} P_n^1(\cos\theta) \tag{2.12}$$

2. Scattering Cross Section

The radar cross section of a target is a quantitative measure of the ratio of power density in the vector signal scattered in the direction of the receiver to the power density of the radar wave incident upon the target [Ref. 8]. The vectoral nature of the scattering interaction requires specification of the transmitter polarization and receiver polarization with reference to target orientation in three dimensions. Transmitter operating frequency must also be specified. The radar or back scattering cross section is usually defined to be independent of range to the target, but it depends upon target shape and material, the angle at which the target is viewed, radar frequency, and the polarization of the transmitting and receiving antennas. Independence of the back scattering cross section upon the range to the target is valid under the far-field condition, i.e., when the target is sufficiently far from the transmitting antenna to justify the assumption that the incident wave is planar in the neighborhood of the receiving antenna.

The conventional definition of the scattering cross section in terms of the electric field can be,

$$\sigma(\Theta,\Phi) = \lim_{R\to\infty} 4\pi R^2 \left|\frac{\vec{E}^s}{\vec{E}^i}\right|^2 \qquad (2.13)$$

where $R \equiv r$ is the distance from receiving antenna to target. Particularly for the back scattering $\Phi = 0$, $\Theta = \Pi$, and for the perfectly conducting sphere $|m|\to\infty$. Hence,

$$a_n = \frac{\Psi_n'(\alpha)}{\zeta_n'(\alpha)} \quad , \quad b_n = \frac{\Psi_n(\alpha)}{\zeta_n(\alpha)} \qquad (2.14)$$

Equation for $S_2(\Theta)$ yields,

$$S_2(\pi) = -i\sum_{n=1}^{\infty}(-1)^{n-1}\frac{(n+1/2)}{\zeta_n(\alpha)\zeta_n'(\alpha)} \qquad (2.15)$$

because of,

$$\Psi_n(x) = \left(\frac{\pi x}{2}\right)^{\frac{1}{2}} J_{n+\frac{1}{2}}(x) \quad , \quad \zeta_n(x) = \left(\frac{\pi x}{2}\right)^{\frac{1}{2}} H^{(1)}_{n+\frac{1}{2}}(x)$$

$$\pi_n(-1) = (-1)^{n+1}\frac{n(n+1)}{2} \quad , \quad \tau_n(-1) = (-1)^n\frac{n(n+1)}{2}$$

Equation (2.10) now yields,

$$-E_\Theta = E_x^s = E_0 \frac{e^{ik_2 r}}{k_2 r} \sum_{n=1}^{\infty} (-1)^{n-1} \frac{(n+1/2)}{\zeta_n(\alpha)\zeta_n'(\alpha)}, \quad E_\Phi = 0 \qquad (2.16)$$

Finally, back scattering cross section and the phase shift can be obtained as,

$$\sigma_B = \lim_{R\to\infty} 4\pi R^2 \left|\frac{\vec{E}^s}{\vec{E}^i}\right|^2 = \frac{4\pi}{k^2}\left|\frac{\sum_{n=1}^{\infty}(-1)^{n-1}(n+\frac{1}{2})}{\zeta_n(ka)\zeta_n'(ka)}\right|^2 \qquad (2.17)$$

where $k_2 = k$, $\alpha = ka$

$$\text{Phase} = -\arg\left\{\frac{\sum_{n=1}^{\infty}(-1)^{n-1}(n+\frac{1}{2})}{\zeta_n(ka)\zeta_n'(ka)}\right\} \qquad (2.18)$$

For almost any finite target, an examination of the scattering cross section as a function of frequency leads to a separation of the frequencies into three regions each of which is characterized by a particular type of behavior [Ref. 9]. There is, first of all, the LF region where the cross section increases rapidly and smoothly with fourth power of frequency. This Reyleigh-region behavior is characteristic of any object whose greatest dimension is much smaller than a wavelength. Figure 2.3 shows the variation of radar cross section with the ratio of sphere circumference to wavelength, $2\pi a/\lambda$, where "a" is the sphere radius [Ref. 10].

Increase in frequency, (or normalized circumference $2\pi a/\lambda$, for sphere) introduces oscillations in the cross section curve which damp rapidly with increasing $2\pi a/\lambda$ and which vary about a mean value $\sigma/\pi a^2 = 1$ .The region where these oscillations are prominent $(1<2\pi a/\lambda<10)$ is called Mie or resonant region, as mentioned earlier. Even for $ka = 2\pi a/\lambda = 43$ cross section is still varying by ±1% about

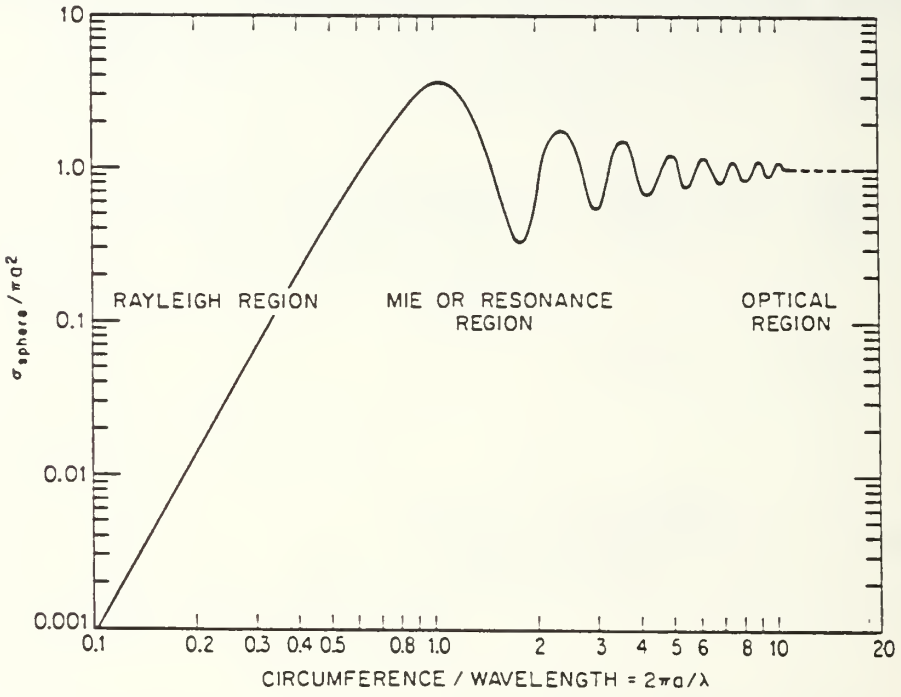

Figure 2.3 Radar Cross Section of the Sphere

its mean value.

In the high-frequency limit ($ka>10$), known as optical region, the cross section settles down to the specular value $\sigma = \pi a^2$, the projected area of the sphere.

III. MEASUREMENTS AND RESULTS

The value of experimental radar cross section work is necessary and quite obvious when one realizes that we have exact solutions for the scattering from only a few bodies, although there are, of course, excellent approximate solutions for several simple shapes. Much emphasis is placed on approximate solutions in studying radar cross sections, and experimental results have been very important in helping to develop such solutions and in providing their validity.

The principal difficulties experienced in measuring radar scattering cross sections are in the separation of the transmitted signal from the received signal and the elimination of unwanted signals that are reflected from the background, foreground, and the target model support.

Radar cross section measurement facility at the Naval Postgraduate School utilizes CW system that depends entirely on cancellation the unwanted signals. The CW system, probably the most reliable, is particularly useful for small models that are measured at ranges of 15 meters or less.

This chapter deals with the description of the above system, its experimental setup, measurement procedures, as well as the validation of the obtained measurement data, in great detail.

A. EXPERIMENTAL SETUP

The configuration of the entire system is shown in Figure 3.1. System is divided into three basic parts as follows:

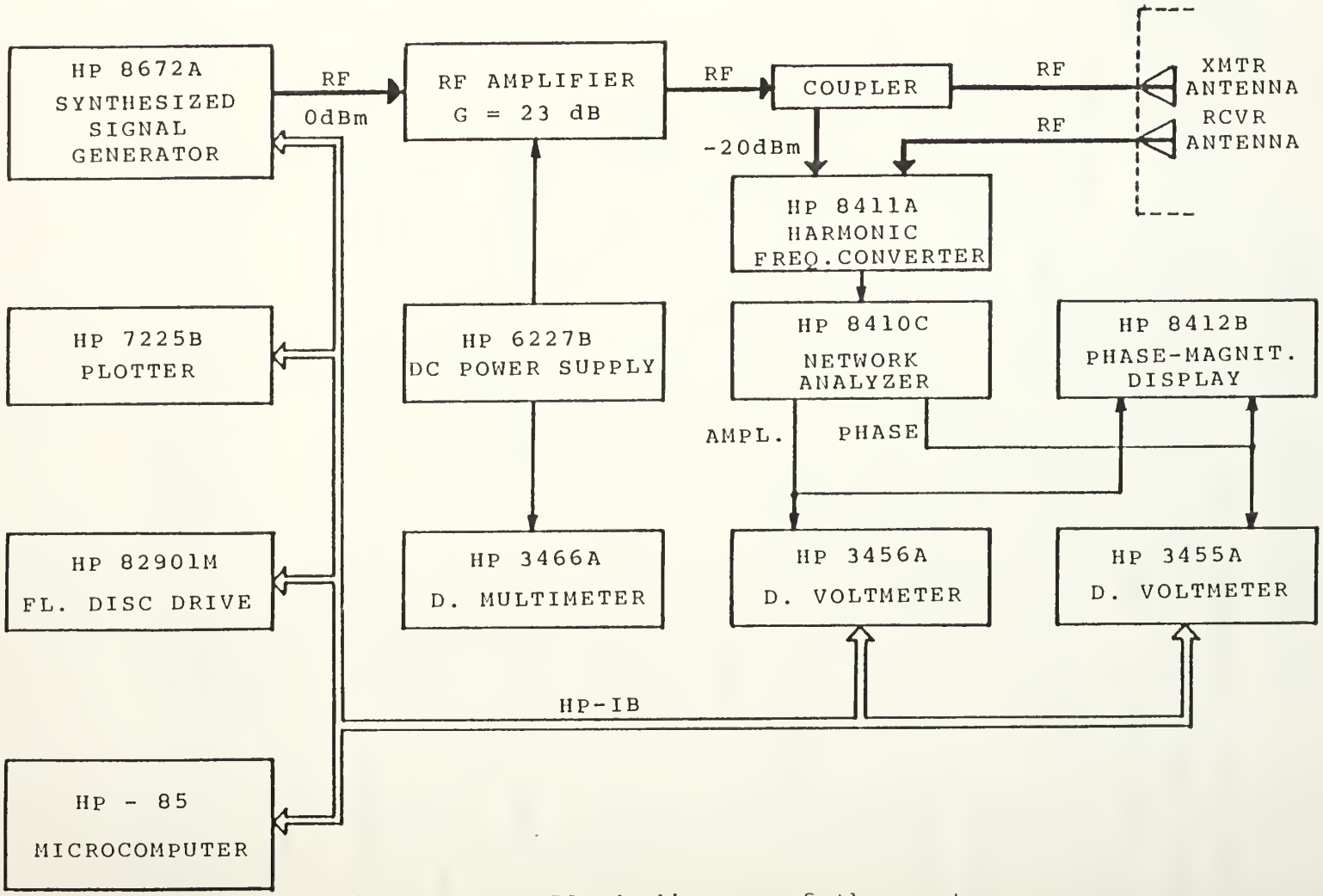

Figure 3.1 Block diagram of the system

1. Range Geometries

The physical arrangement of the transmitting and receiving antennas, target mount, walls, etc. is usually

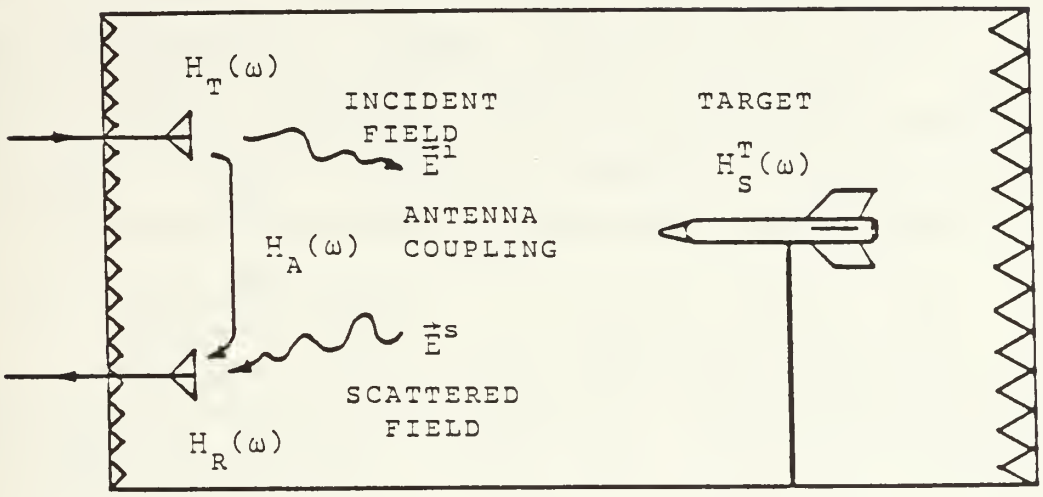

Figure 3.2 Anechoic Chamber at Naval Postgraduate School

called the range geometry. A variety of range geometries have been developed: these are characterized by the way they have been designed to help eliminate unwanted signals reflected from the foreground and background [Ref. 11]. The range geometries commonly used are free field ranges with the antenna beams horizontal, oblique, or vertical; ground plane ranges, and image plane systems. Free space and image plane ranges are commonly used in both indoor and outside.

The new "free-field" CW scattering range at the Naval Postgraduate School imploys a metallically shielded anechoic chamber Figure 3.2, [Ref. 14]. It can also serve as the free-field video impulse scattering range [Ref. 13]. Physical dimensions of the anechoic chamber are approximately: length 6m, width 3m and height 3m. Anechoic chamber

has the very important advantage of being free from time varying interference due to external noise such as atmospheric noise, man-made noise (radio, TV, radar, etc.), as well as the weather conditions. This advantage is obtained at the expense of introducing critical problems that arise with reflections from the side walls, ceiling, and back wall. These reflections are reduced by lining the interior of the chamber with EM waves absorbers. EHP-8 microwave absorber made by Rantec Inc.is utilized which is designed for wide range of frequencies above 1.5 GHz. The units are fabricated of high quality urethane foam which is cut into a precise pyramidal configuration for front and back walls, and wedge configuration for lateral walls, floor and ceiling. Continuing improvement in absorber performance and chamber design and in electronic schemes for eliminating unwanted reflections have made it possible to make measurements on practically all types of targets except those that are too large to be compatible with the chamber dimensions.

TABLE I

Antenna Specifications

Frequency range	4 - 18 GHz
Gain	6 - 12 dB
VSWR (maximum)	3.2 : 1
Isolation	<20 dB below 5.5 GHz
	>20 db above 5.5 GHz

The target is supported by a low cross section Styrofoam column to minimize reflections [Ref. 12]. Detailed analysis of the support influence is given in section "C" of this chapter.

The Naval Postgraduate School radar cross section range operates as bistatic system utilizing two horn

antennas. Both transmitting and receiving antennas are mounted on a removable panel in the front wall. Base aluminum plate that bears both antennas has mechanism allowing antenna adjustment in all three axes. Adjustment screws are accessible from outside the anechoic chamber providing beam steearing toward target. Antennas are designed for both, linear polarizations, horizontal and vertical. While used as horizontally polarized, transmitter and receiver, the other feeds are terminated with matched loads and vice versa for the vertically polarized feeds. Basic antenna characteristics are given in the Table I.

2. Instrumentation

Equipment used in the scattering laboratory of the Naval Postgraduate School, shown in the block diagram Figure 3.1, are listed below:

- Microcomputer HP-85
- Synthesized Signal Generator HP 8672A
- Harmonic Frequency Converter HP 8411A
- Network Analyzer HP 8410C
- Phase-Magnitude Display HP 8412B
- RF Amplifier
- DC Power Supply HP 6227B
- Digital Multimeter HP 3466A
- Digital Voltmeter HP 3456A
- Digital Voltmeter HP 3455A
- Flexible Disc Drive HP 82901M
- Plotter HP 7225B
- HP Interface Bus
- Directional Coupler
- Coaxial Cables

HP-85 microcomputer provides necessary signal processing using developed computer codes, controls Hp 8672A

signal generator, both HP 3456A and HP 3455A digital voltmeters, as well as the HP 82901M disc drive and HP 7225B plotter. Communication between microcomputer and remote controled devices takes place through HP Interface Bus (HP-IB).

The HP Model 8672A synthesized signal generator produces RF oscillation in a frequency range of 2 to 18 GHz. The output is leveled and calibrated from +3 to -120 dBm. AM and/or FM modulation modes, and most other modes can be remotely controled using the HP-IB programming format.

Rf signal from signal generator enters the microwave amplifier whose gain is 23 dB. Because of the low level output from signal generator, amplification is necessary in order to obtain satisfactory S/N ratio in the receiver output of the target return at higher frequencies. The power supply (HP 6227B) provides the amplifier with a DC voltage and the digital multimeter (HP 3466A) monitors that voltage.

Passing through directional coupler, the Rf signal is split into two. Unattenuated RF portion feeds transmitting horn antenna and the other portion is attenuated by 43 dB and feeds the reference port of the harmonic frequency converter. The test port input of the converter is fed by the return signal collected with the receiving horn antenna.

The HP 8411A harmonic frequency converter and the HP 8410C network analyzer convert the RF signal being measured to 278 kHz signals that have the same magnitude and phase relationships. These two units together with the HP 8412B phase-magnitude display, function as a phasemeter and a ratiometer for direct, continuous, simultaneous phase and magnitude ratio measurement of RF voltages. The complete network analyzer measures phase angles 0 to 360 and magnitude ratios in decibels over a dynamic range of 60 dB. Harmonic frequency converter automatically tracks the frequency of the signal applied to the reference input.

The magnitude and phase DC voltages, taken from the phase-magnitude display unit, are measured by the HP 3456A and HP 3455A digital voltmeters respectively. Those are versatile digital voltmeters with AC, DC, OHMS, and math functions, and offer the capability of remote programming.

3. Targets

Targets used in this measurement are several aluminum and steel spheres of different diameters and series of right circular cylinders of various lengths and diameters, made of thin walled brass and stainless steel. Spheres are used for calibration as canonical or standard targets of known (computed) radar cross sections. This measurement reveals correlations of the theoretically obtained results using the Mie series given by the equations (2.17, 2.18). Cylinders, as primitive models of the missiles, are used to form necessary data base for future work. Adding caps, fins and wings, this primitive model will be perturbed toward a real missile body. Exhaustive measurements of radar cross section and phase shift will be taken out, and results should reveal versatility of this scheme in its application to target identification and radar cross section reduction.

One advantage of the radar range, as mentioned earlier, is the practicability of testing models that are smaller and cheaper than full-scale targets. For this purpose the radar wavelength is scaled by the same factor as the dimensions of the model. If "D_0" is any given dimension of the target, and "D_M" is the equivalent dimension of the model, the following scaling relation is employed,

$$p = \frac{D_o}{D_M} = \frac{\lambda_0}{\lambda_M} \qquad (3.1)$$

where λ_M is the wavelength used for the measurement and λ_O is the wavelength for which the target cross section is required. At the same time, the measured cross section of the model σ_M should be multiplied by p^2 to give the target cross section σ_O,

$$\sigma_O = \frac{\lambda_O^2}{\lambda_M^2} \sigma_M = p^2 \sigma_M \qquad (3.2)$$

Exact scaling requires the model conductivity to be equal the target conductivity multiplied by the ratio "p". This parameter is not critical if the model conductivity is high enough.

B. MEASUREMENT PROCEDURE

Procedure for measuring back scattered electric fields from a target was suggested in chapter II. Metallic spheres are commonly used as standards since their cross section can be computed, equation (2.17). Prior to the start of taking measurements on various targets, system transfer function has to be obtained through a calibration program.

1. Calibration of the System

After run of the calibration program, microcomputer HP-85 remotes and initializes all programable units, Figure 3.1. Signal generator is set on and begins to generate RF energy. This RF, CW signal undergoes 23 dB amplification in order to improve S/N ratio. It passes directional coupler and is radiated, by the transmitting antenna, toward the target into the anechoic chamber. Signal return at the cms receiving antenna, which is the vectoral sum of the target echo and the background radiation is picked up by the receiving antenna which feeds the "test" port of the

harmonic frequency converter. The background radiation includes the direct coupling between the two antennas and the back scattered signal from the chamber. The "reference" port of the same instrument is feed with the RF signal passed through another branch of the directional coupler. This signal is attenuated by 43 dB and enters the frequency converter at the about -20dBm. The converter translates the RF signals being measured to 278 kHz while preserving the same magnitude and phase relationships. It also tracks automatically any change in frequency applied to its reference port, and passes that signal to the network analyzer. The frequency converter, the network analyzer together with the phase-magnitude display unit function as a phasemeter and a ratiometer for direct, continuous, simultaneous phase and magnitude ratio measurement of RF voltages, as mentioned earlier. Both magnitude and phase of the signal return are measured by the HP 3456A and HP 3455A digital voltmeters respectively, and stored in the HP-85 microcomputer which then computes the real and imaginary parts of the signal. Separation of the target echo from the background radiation can be accomplished by measuring the background radiation data as will be explained latter.

The procedure repeats "NO" times at each frequency, and after the average value of magnitude and phase are computed, the signal generator increments frequency by one step, and the system goes through new cycle.The block diagram of Figure 3.3 presents various transfer functions of the scattering range [Ref. 13], [Ref. 14]. Those are:

- $H_T(\omega)$ - Transfer Function of the Transmitting Circuit
- $H_R(\omega)$ - Transfer Function of the Receiving Circuit
- $H_A(\omega)$ - Antenna Coupling
- $H_C(\omega)$ - Clutter Signal From the Anechoic Chamber

- $H_S^C(\omega)$ - Back Scattered Signal Normalized ($|H(\omega)|^2$ is the cross section and $\arg[H(\omega)]$ is the phase shift of the target)
- $H_S^T(\omega)$ - Back Scattered Signal of an Arbitrary Target

Besides, $X(\omega)$ is input signal provided by the signal generator and the RF amplifier. $Y(\omega)$ is reading of the network analyzer. The network analyzer provides the ratio $Y(\omega)$ of the test channel signal to the reference signal which is a complex number at each frequency step. Note that every block, including $X(\omega)$ contains noise.

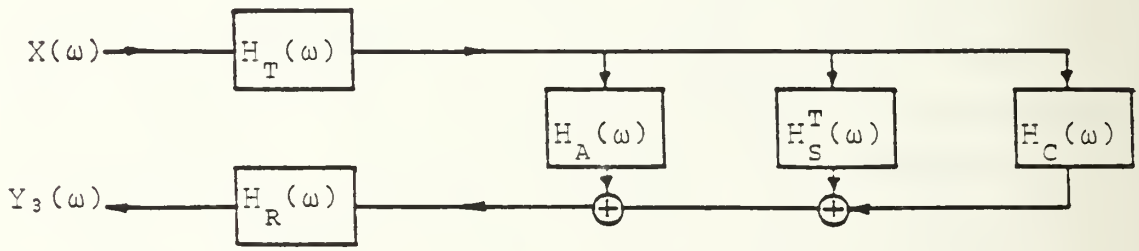

Figure 3.3 System Representation with Target in Place

The system transfer function $H_{sys}(\omega)$ and the target back scattering $H_S^T(\omega)$ can be found by performing three separate measurements:

1. without the target in place
2. with the canonical target in place
3. with the arbitrary target in place

From the first measurement, background data (response from the chamber without target in place) are obtained. Block diagram of Figure 3.4 represents this measurement.

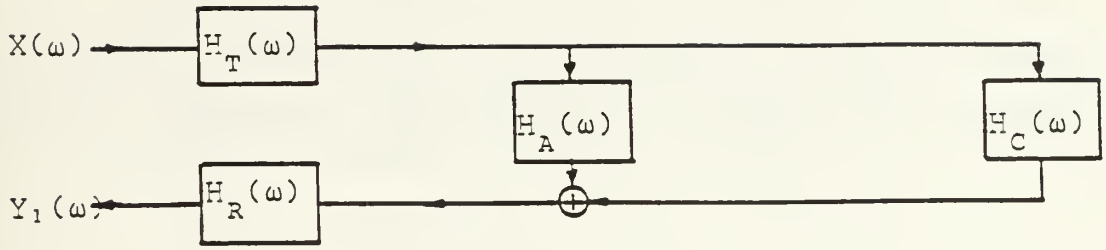

Figure 3.4 System Representation in Background Measurement

Signal return $Y_1(\omega)$ which corresponds to the scattered signal of the background can be expressed by the equation (3.3).

$$Y_1(\omega) = H_T(\omega)\{ H_A(\omega) + H_C(\omega) \} H_R(\omega) \qquad (3.3)$$

The procedure described above is utilized in the second measurement as well, in order to acquire data with the sphere as canonical target in place. For this case system response is labeled as $Y_2(\omega)$ and the measurement is represented with the block diagram of Figure 3.5. Equation (3.4) represents this configuration.

These two measurements provide system calibration because system transfer function can be found:

$$Y_2(\omega) = H_T(\omega)\cdot\{H_A(\omega) + H_S^C(\omega) + H_C(\omega)\}\cdot H_R(\omega) \qquad (3.4)$$

Subtracting background given by equation (3.3) from the data obtained from canonical target given by equation (3.4)

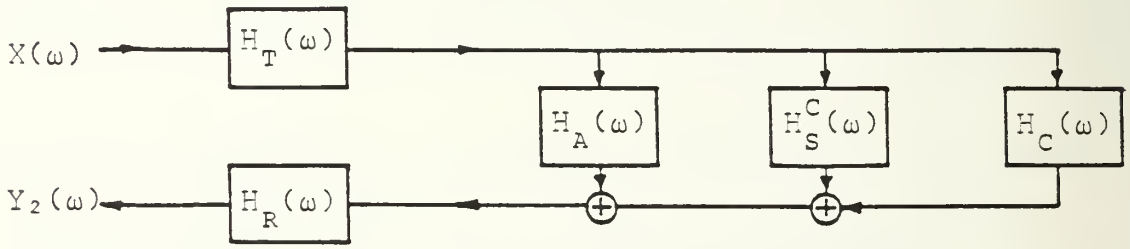

Figure 3.5 System Representation with Canonical Target

yields scattered data from the sphere (reference standard). Let it be $Y_4(\omega)$:

$$Y_4(\omega) = Y_2(\omega) - Y_1(\omega) = H_T(\omega)H_S^C(\omega)H_R(\omega) \qquad (3.5)$$

In equation (3.5) $H_S^C(\omega)$ can be obtained from Mie solution, equation (2.17). Equation (3.5) yields $H_{sys}(\omega)$ as complex function of frequency "ω" :

$$H_{sys}(\omega) = \{ H_T(\omega)\, H_R(\omega) \}^{-1} = H_S^C(\omega) Y_4(\omega)^{-1} \qquad (3.6)$$

After the calibration of the system is completed and its transfer function $H_{sys}(\omega)$ obtained, we can find the scattered field for any arbitrary target. To accomplish this, we have to perform a third measurement with the target in place. System representation is given on the block diagram of Figure 3.3 and its mathematical interpretation is as follows:

$$Y_3(\omega) = H_T(\omega) \{H_A(\omega) + H_C(\omega) + H_S^T(\omega)\} H_R(\omega) \qquad (3.7)$$

The background data $Y_1(\omega)$ are subtracted from the target data $Y_3(\omega)$ which we call $Y_5(\omega)$,

$$Y_5(\omega) = Y_3(\omega) - Y_1(\omega) = H_T(\omega) H_S^T(\omega) H_R(\omega) \qquad (3.8)$$

Target transfer function $H_S^T(\omega)$is obtained by simply pluging equation (3.6) into equation (3.8). It yields :

$$H_S^T(\omega) = Y_5(\omega)\, H_{sys}(\omega) \qquad (3.9)$$

Radar or back scattering cross section can be computed as :

$$\sigma_B = |H_s^T(\omega)|^2 = |Y_s(\omega)\ H_{sys}(\omega)|^2 \qquad (3.10)$$

where $|H_S^C(\omega)|^2 = \sigma_{TH}$ is theoretically computed back scattering cross section of the sphere used as reference standard. The phase shift of the target is :

$$\text{Phase Shift} = \arg\{Y_s(\omega)\} + \arg\{H_{sys}(\omega)\} \qquad (3.11)$$

2. Measurement on Spheres and Cylinders

Measurement procedures for both calibration and a target data acquisition are similar as was described in previous section and consists of three steps. After calibration data from several spheres are obtained and compared with the computed results of the respective target. For that purpose, theoretical results were obtained using Mie solution, given by the equation (2.17), and represented in graphical form , Figures 3.7 to 3.13. Computer plots of target cross section and phase were taken for three spheres of different diameters, in the frequency range of 2 to 18 GHz, incrementing frequency in steps of .02 GHz. For the first part of the experimental work, the targets used were spheres and in the second part were cylinders. All targets are labeled with numbers 1 through 8 for convenience. Besides, brief description of each target is given in the header of the corresponding graph. It contains basic physical dimensions of the target, and corresponding measurement specifications such as the polarization of the antennas and the sphere used for calibration. A brief review of the targets characteristics is given in Table II. All graphs of

theoretical computations and experimental results are given at the end of this chapter.

TABLE II

Target Characteristics

TARGET1	Sphere ,	made of alum.,	D = .875" .	
TARGET2	Sphere ,	made of steel,	D = 1.125".	
TARGET3	Sphere ,	made of steel,	D = 3.187".	
TARGET4	Cylinder,	made of brass,	D = .75" ,	L = 3.875".
TARGET5	Cylinder,	made of steel,	D = .75" ,	L = 3.875".
TARGET6	Cylinder,	made of brass,	D = .5" ,	L = 3".
TARGET7	Cylinder,	made of brass,	D = .375" ,	L = 1.875".
TARGET8	Cylinder,	made of brass,	D = .75" ,	L = 6".

Measurements on spheres and cylinders were done for a frequency range of 10 to 15 GHz in steps of 0.1 GHz. Graphs of target cross section and phase versus frequency are represented by dots overlayed with corresponding theoretical curves.

C. VALIDATION OF MEASUREMENT DATA

Recognition of sources of errors in measurement data is usually difficult. In a few special cases, it is possible to recognize the presence of error and determine its source by observing the deviation of a target cross section vs. frequency plot from anticipated behavior. The most common difficulties are system noise and target-range problems. The latter include 1). the requirement that the field incident on the target (model) be a reasonable approximation to a uniform plane wave over the volume of space occupied by the

scattering object, 2). the interference of extraneous reflections from objects other than target, and 3). method of supporting the target [Ref. 12], [Ref. 15]. Each of these problems as well as their effect to the measurement results will be discussed separately.

1. System Noise

The main sources of the system noise come from the RF amplifier, the network analyzer and from thermal noise in the Rf signal path and the electronic circuitry. By using the anechoic chamber which is metallically shielded, almost all external noises were eliminated. The noise from the Rf amplifier is present in $Y(\omega)$ because the test channel signal is a combination of signals output from the amplifier at different instances while the reference channel signal left the amplifier at a particular instance. Thus their ratio will contain time varying noises.The network analyzer is a noise source because for every set of target data obtained, the generator steps through the frequency several times.At one frequency, the frequency converter may not pick the same harmonics each time the generator steps on this frequency.This causes variations in the network analyzer responses. The other noises are thermal noises. All these components of the system noise sources produce random noises and can be significantly reduced by averaging. Averaging process was done twice, first during the acquisition of the magnitude and phase data at a single frequency. The entire measurement procedure is then repeated three or four times and averaged.

2. Antenna-Target Distance

In general, the fields scattered by an object depend on the variation, in phase and magnitude, of the incident field over the surface of the object as well as on the

object's material, size, and shape [Ref. 16]. The scattering cross section of a target is defined for a plane incident wave and for the far field scattered by the target. Because of the confines of an indoor range, non-plane wave illumination of the target is a significant source of measurement error. The far from an antenna is usually spherical along its boresight axis and can be only an approximation to a plane wave. Such a spherical wavefront, when referenced to a plane perpendicular to the antenna boresight and tangent to the wavefront at the nominal target position, will produce, to the lowest order of approximation, a phase deviating quadratically from that of an ideal plane wave along directions perpendicular to the central ray.The plane wave approximation to the far field is satisfactorily established, as the rule of thumb, for antenna-target distance equal to or greater than $2D^2/\lambda$, where D is the largest dimension of the target (model). This condition as usually imposed relates to the uniformity of the phase front over the lateral region occupied by the target. To preserve both magnitude and phase uniformity within the test region, the magnitude gradient along the antenna boresight should be reduced, as much as possible. Due to reciprocity, the same rule of thumb of $2D^2/\lambda$ as the range for far field applies to the scattered field from the target. To avoid these difficulties, a more stringent far-field condition should be applied. In other words, target should be moved farther from the transmitting antenna.

Initially measurements were done with antenna to target range of 1.5m, that caused disagreement with theory for the spheres 6" in diameter and larger. Distance antenna-to-target was changed to 3m, but the influence of the background, that will be explained latter, as well as S/N ratio caused erroneous results. Finally, an optimal range of 2m was established to satisfy most of, often contradictory requirements.

3. Background Radiation

Accurate target cross section measurements require the background signal to be held at very low level. Background radiation can be defined as returns from objects in the vicinity of the target. Background effects may be classified as direct backscatter and target scatter. Both sources of error are reduced by arranging radar-absorbing material so as to minimize the undesired background signal intensity. Residual direct backscatter can be determined, as it was done in this experiment, by measuring the return in absence of the target.Target scatter, or bistatic coupling effects frequently arise from the strong target-scatter lobes in the forward direction (away from the radar). They characterize many targets and are often two or three orders of magnitude greater than the direct-back scattering which we measure. For instance, a sphere which diameter equals 6" has aforward-scatter about 25 dB stronger than the back scattering cross section [Ref. 17]. Thus the possibility that the scattered energy from the target may illuminate the surroundings to return significant energy to the radar cannot be ignored. Illumination of the background by target-scattered energy may be followed by reradiation direct to the radar or by scattering back to the target and then to the radar.

This target-scatterer effects were not measured in the experiment. Even direct backscatter can not be determined quite accurately because the introduction of the target alters the radar illumination of the background as well, so the background cancellation is no larger complete. The resulting error depends upon the target cross section, and the magnitude of the background before and after the target introduction. It is generally found that the error is small if the radar-to-target distance is small compared with

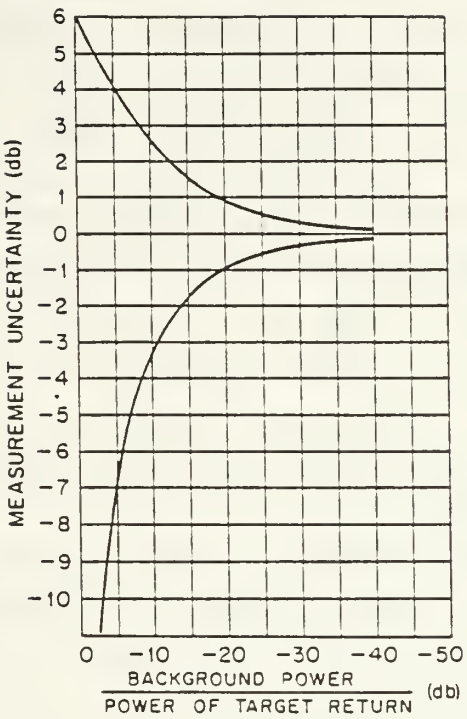

Figure 3.6 Measurement Error Due to Background

both the radar-to-background and target-to-background distances but that it can become large when the target distance is increased. As mentioned earlier, background errors were noticed by taking measurements at distances of 1.5m and 3m.

Figure 3.6 shows the measurement error that can result from the background as a function of the ratio of effective background cross section to target cross section [Ref. 18]. To prevent error greater than 1dB, that corresponds to 20% in cross section, it is necessary that the effective background cross section be less than one hundredth the cross section of the target.

4. Target Supports

Target support, as a structure employed to control and permit measurement of the target position and orientation, is another important source of measurement error. The magnitude of the error introduced depends upon the back scattering from the target support relative to that of the target. The error is significant when the target cross section is small. If interference with the support is suspected, reruns of the experiment with different support configurations frequently reveal changes in both cross section and phase. In the case of the measurements performed on spheres, when the exact solutions and corresponding graphs for the target cross section and phase are known, deviations from those known patterns pinpoint to the errors in the measurements.

Second effect that may occur is modification of the incident field by the support device. This effect, since it represents coupling between the target and its support, is impossible to evaluate quantitatively.

In this work, the effect of the back scattering from the support, as well as the effect of the field modification, were significantly reduced using tapered Styrofoam supports.

Finally, a brief comment on measurement results will be given, along with computer plots of target cross section and phase for all targets, spheres and cylinders.

Measurements on spheres were done to obtain system calibration and reveal its validity for three spheres of 0.875", 1.125" and 3.187". Besides these measurements have shown almost all previously discussed effects on the accuracy of the measurements itself.

Figures 3.13, 3.14 shows target cross section and phase respectively of the 3.187" sphere in diameter.

Immediately after calibration, that same sphere was used as the target. Agreement between measurement and theory is very good, remembering that the effect of the system noise couldn't be eliminated completely as well as the target-scatter background. It is observed that the results change in time because of the random nature of the system noise, and thence the background changes. In the Figures 3.15 to 3.18 same calibration was used and results are not as good as in previous measurement, but they still are within ±8% of the theory. The smaller the target cross section the bigger the deviation. This is in accord with the consideration of the background, S/N ratio and support influence on measurement results.

When the calibration was performed using 1.125" sphere, and the data taken of that sphere and 0.875" sphere respectively, disagreement between measurement and theory became more pronounced. In this case, smaller cross section of the target decreases S/N ratio, background and support effects are more enhanced, that all contributes to the bigger measurement error. Results are presented in Figures 3.19 to 3.22.

Influence of the target support reflections and coupling are revealed in Figures 3.23, 3.24 in comparison to the Figures 3.13, 3.14. This time TARGET3 (3.187" sphere) was used for calibration and to obtain target data as well, but with the cylindrical support instead of original one that was tapered. Both cross section and phase are changed slightly. If the target was sphere of smaller cross section, this effect would have been more noticable.

Measurements on cylinders were done using 3.187" sphere for system calibration (CAL3). Same frequency range , as for the spheres, from 10 to 15GHz was chosen, with frequency increments of 0.1 GHz. Measurement results are plotted with solid lines to reveal approximate shape of the

target cross section and phase shift. Results obtained in several different measurements, separated in time, were reproducible and thence could be basis for future work on the perturbation of a cylinder to a missile body.

Figures 3.27 to 3.30 show radar cross section and phase for two cylinders of the same dimensions, but made of two different materials, brass and stainless steel. Objective was to show influence of conductivity on the changes in target cross section and phase shift. This effect couldn't be observed because the both targets are made of materials with comparable , very high conductivity.

In the Figures 3.31 to 3.36 targets were cylinders of different diameters and lengths. Corresponding graphs show that the cross section patterns depend upon cylinder diameter only (number of resonances is the same), while the target length along with its diameter contributes to the absolute value of the cross section. Phase on the other hand depends only upon the cylinder diameter.

Changed polarization from horizontal to vertical gave quite different results for TARGET4 and TARGET6 in comparison to those of horizontal polarization obtained for the same targets, as was expected. Figures 3.36 to 3.40 present these results.

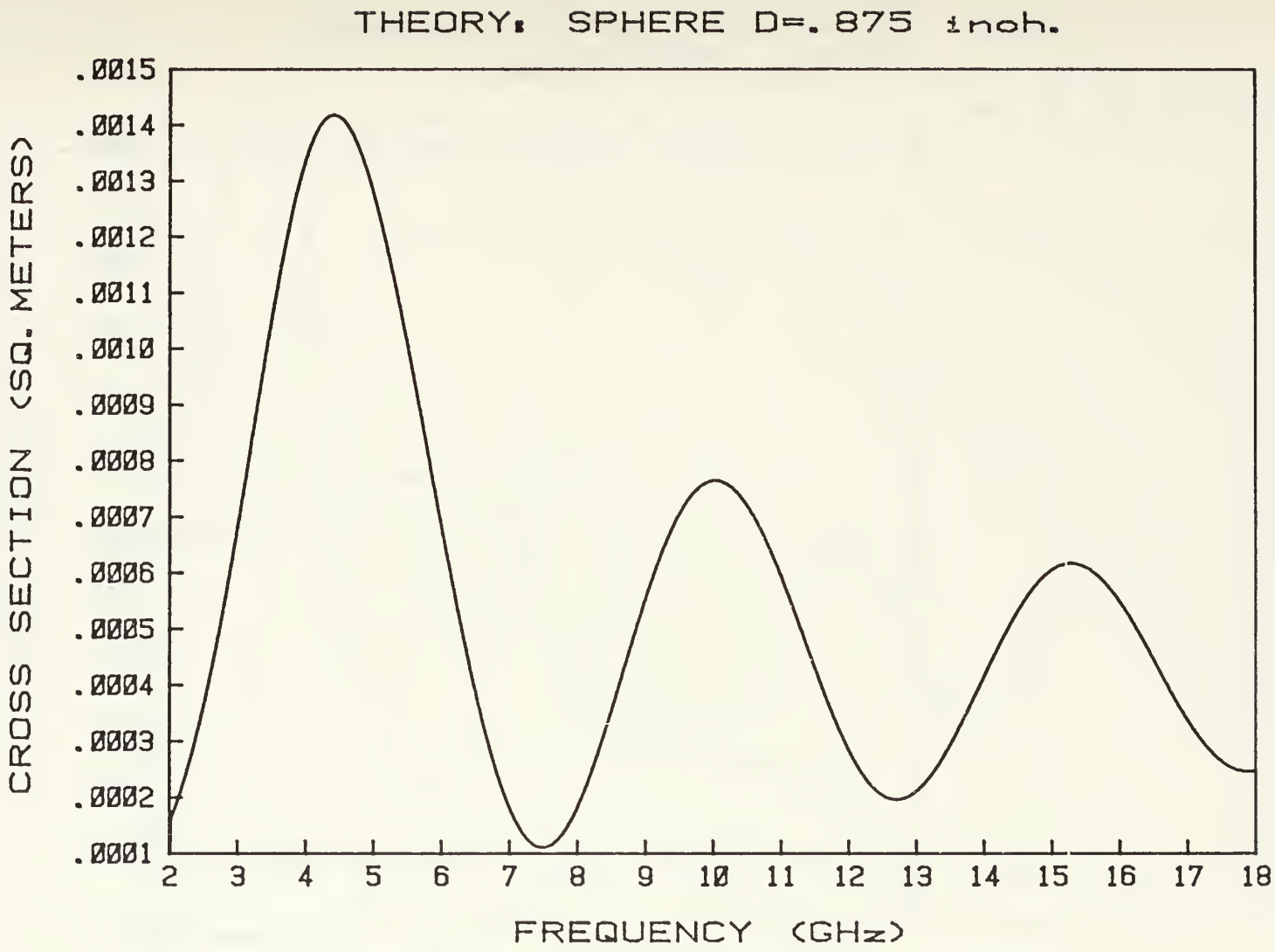

Figure 3.7 TARGET1 - Cross Section (Theory)

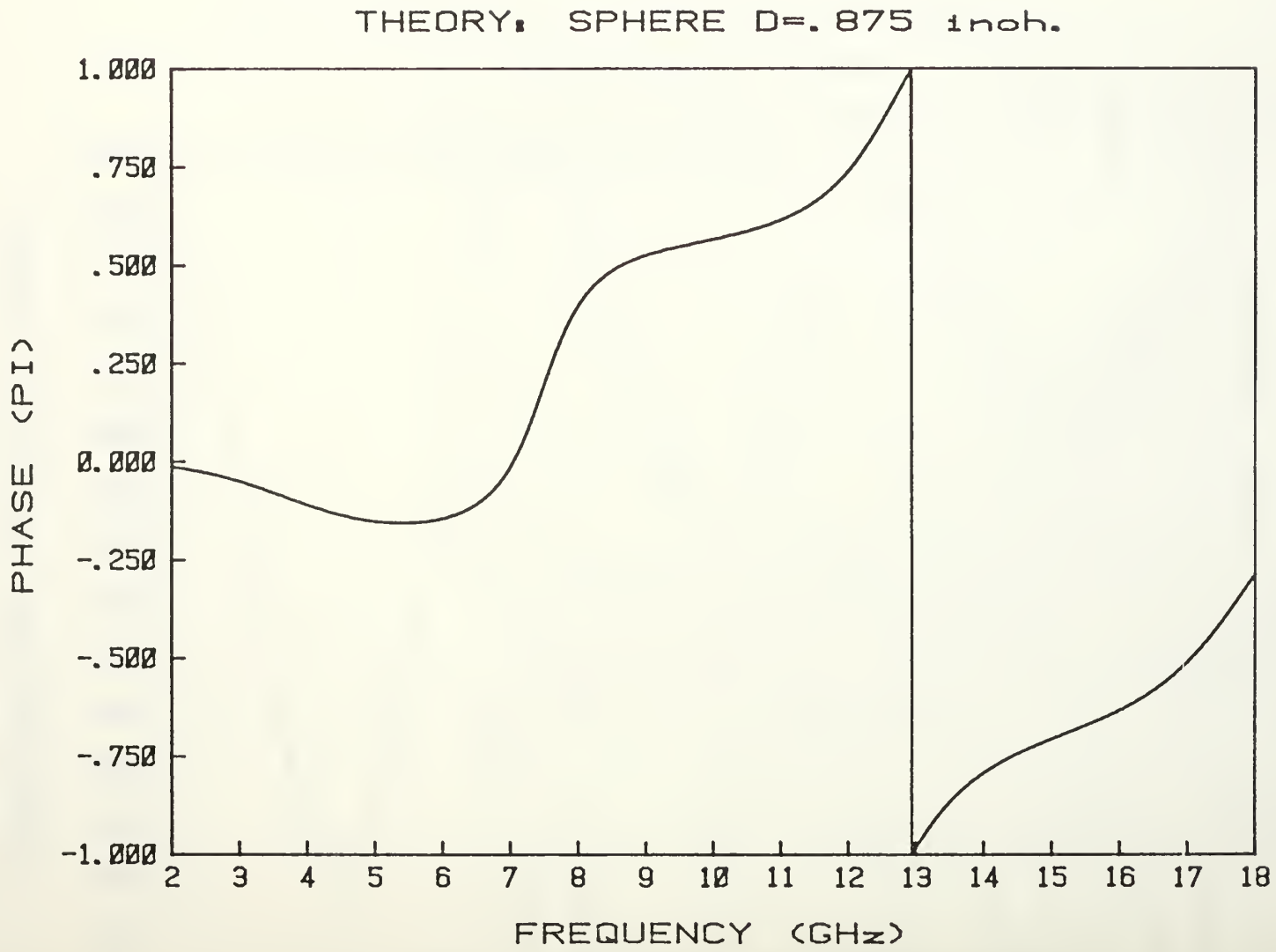

Figure 3.8 TARGET1 - Phase (Theory)

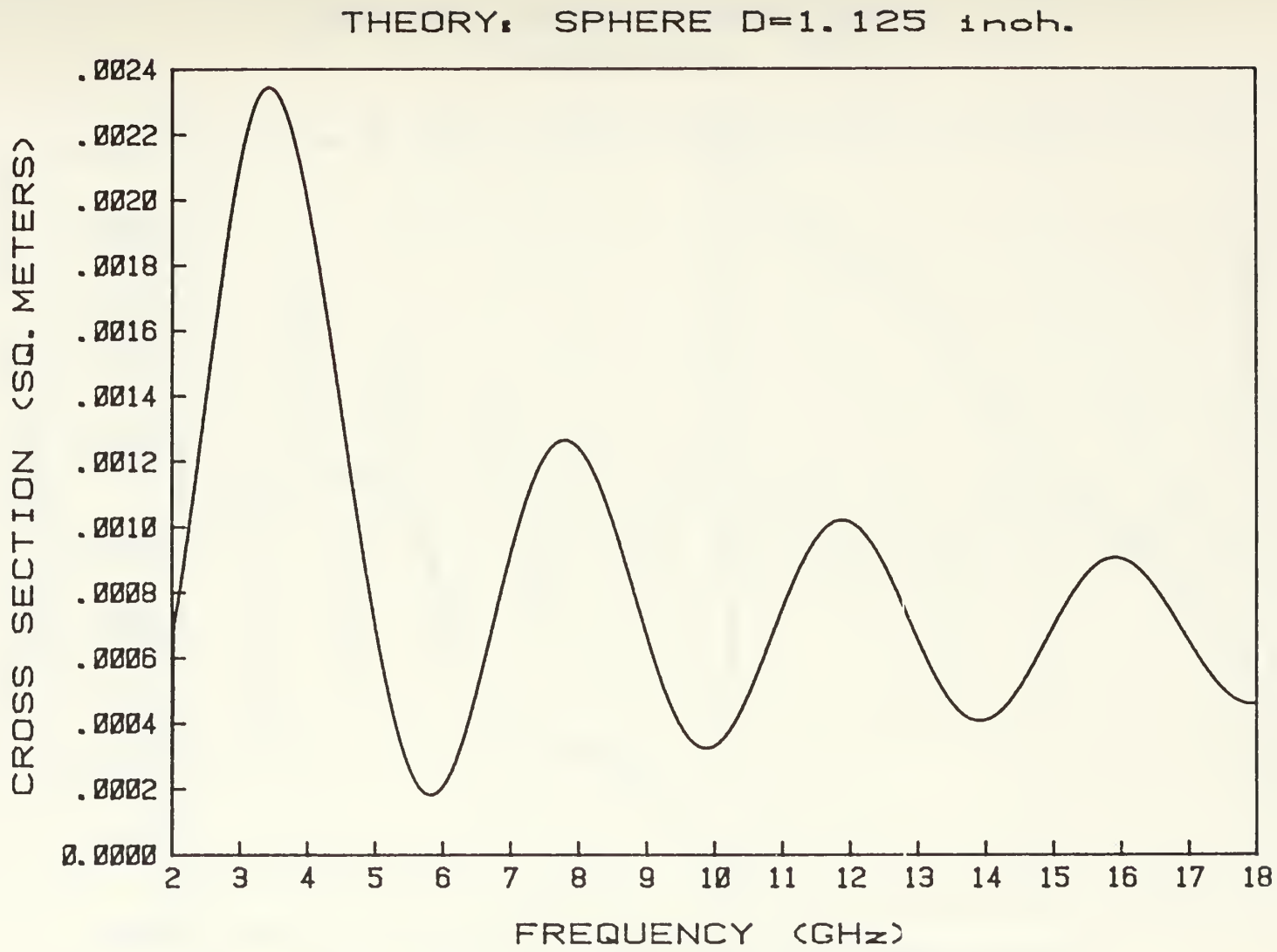

Figure 3.9 TARGET2 - Cross Section (Theory)

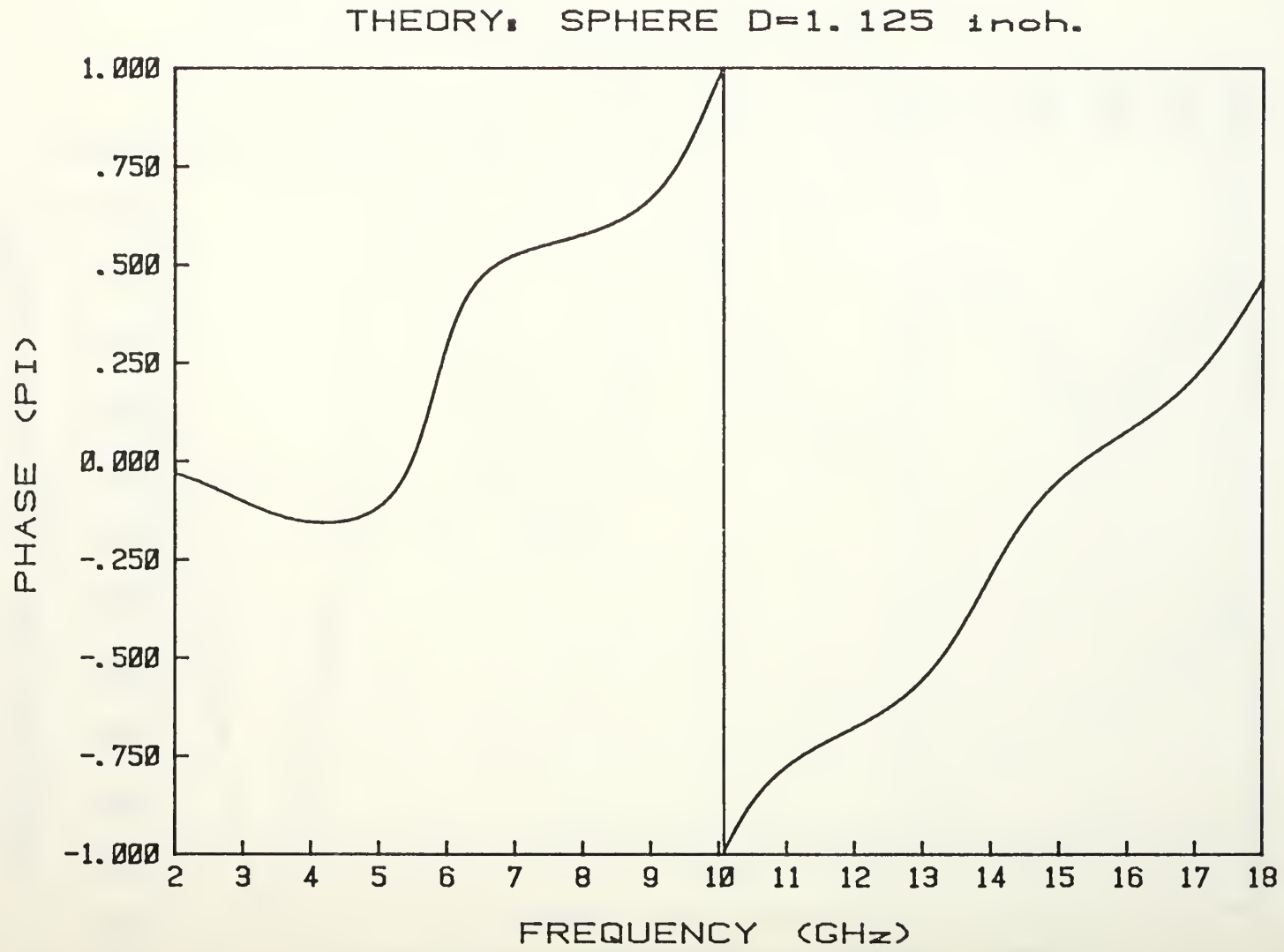

Figure 3.10 TARGET2 - Phase (Theory)

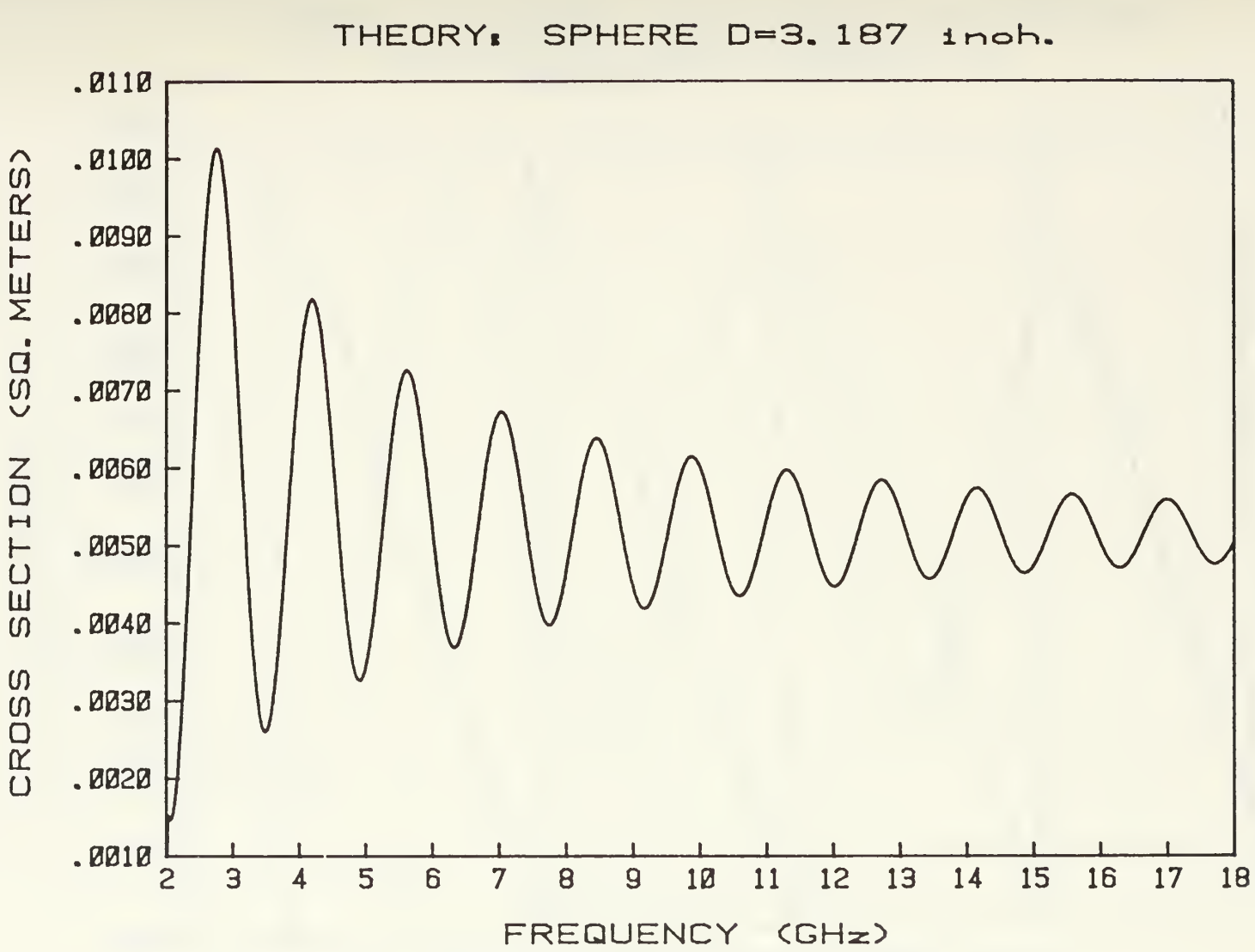

Figure 3.11 TARGET3 - Cross Section (Theory)

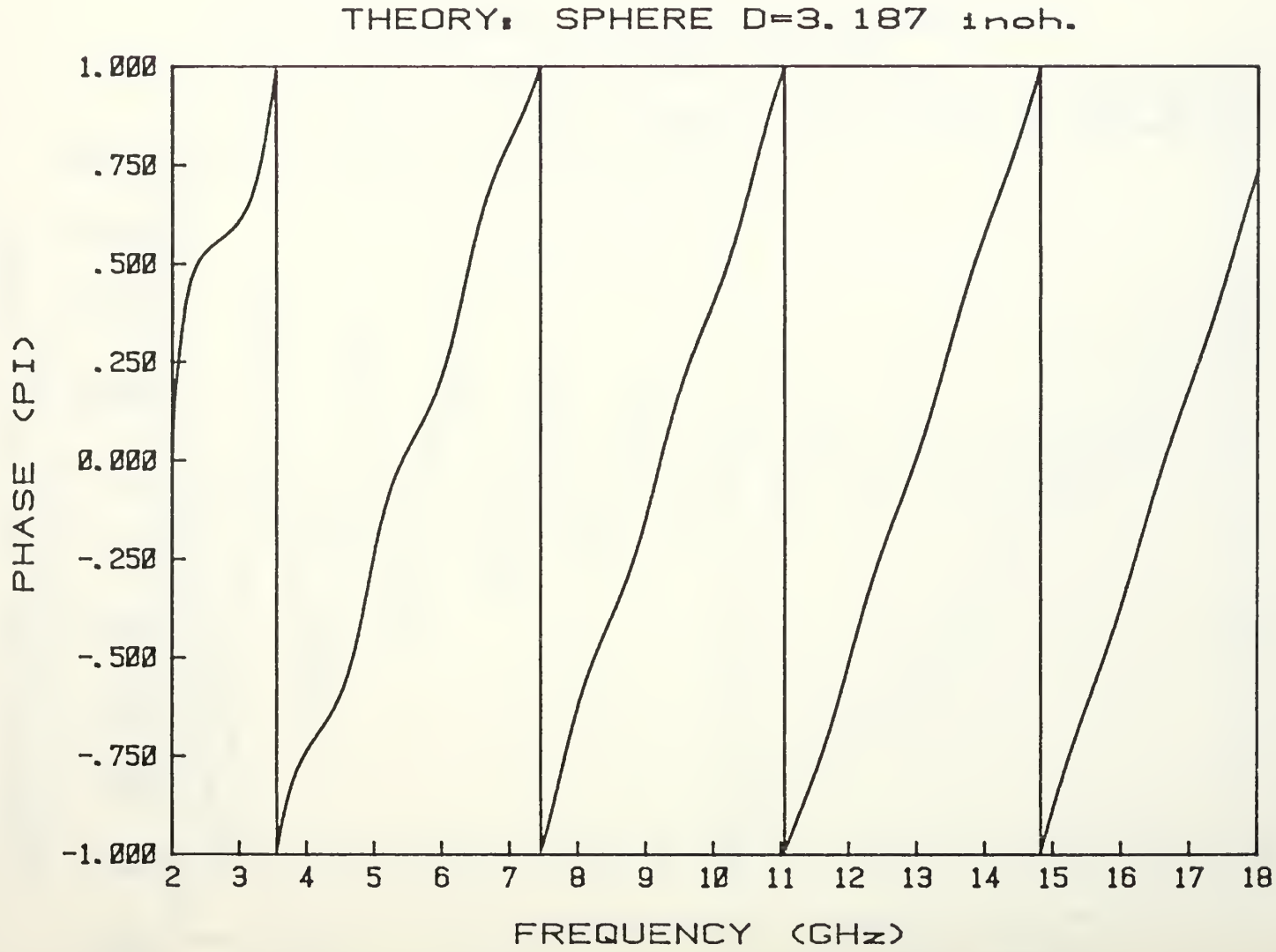

Figure 3.12 TARGET3 - Phase (Theory)

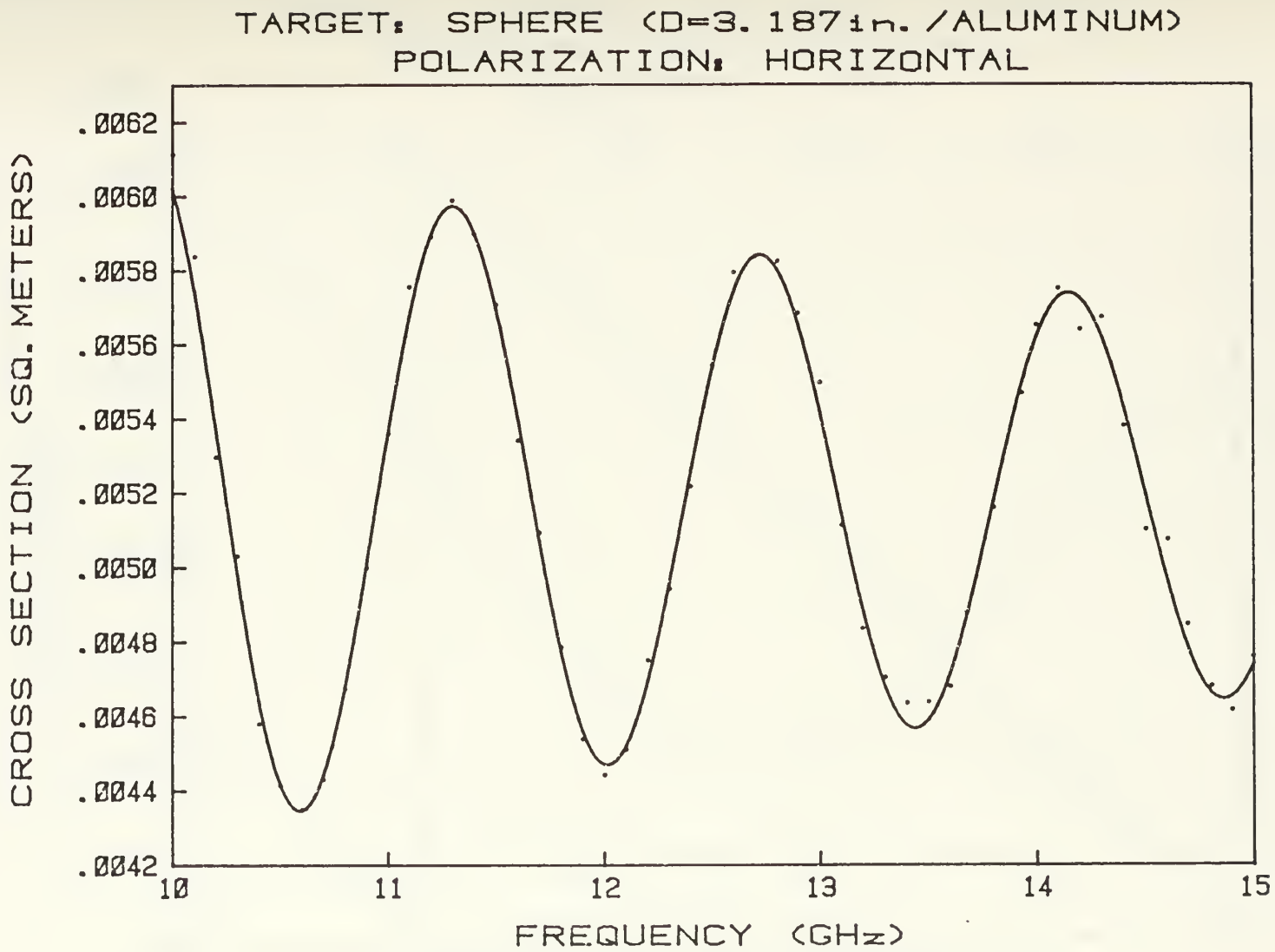

Figure 3.13 TARGET3 - Cross Section

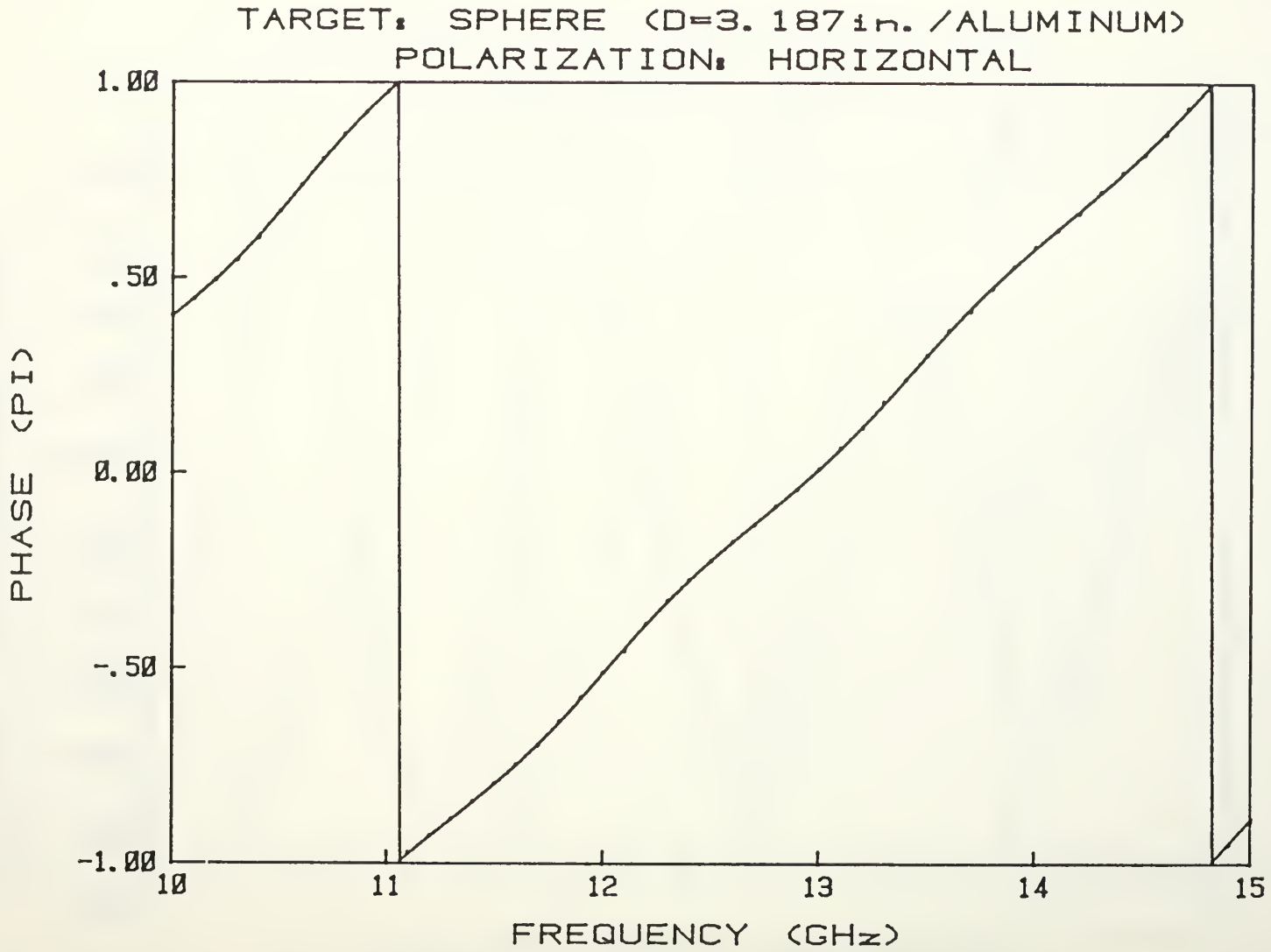

Figure 3.14 TARGET3 - Phase

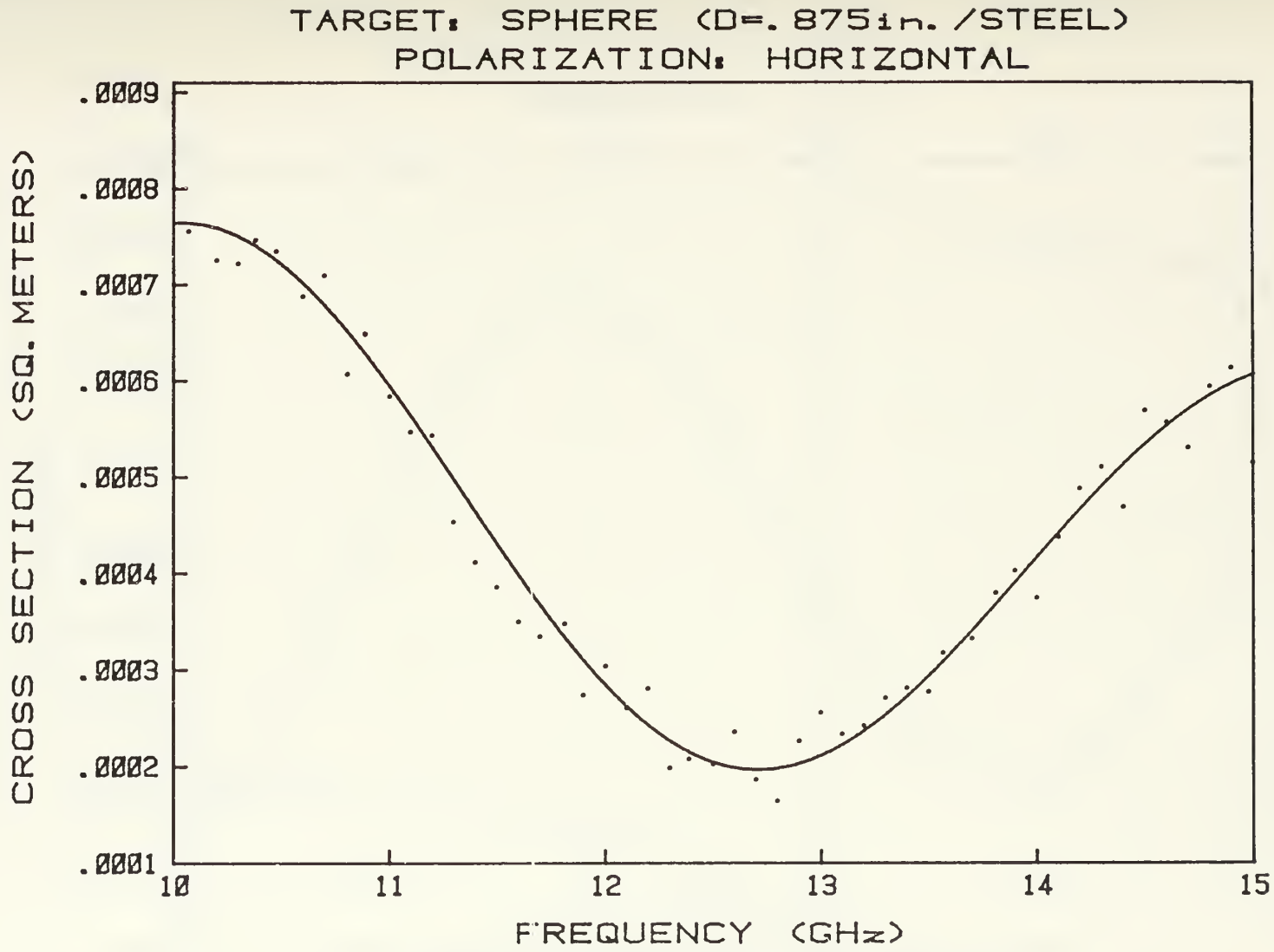

Figure 3.15 TARGET1 - Cross Section

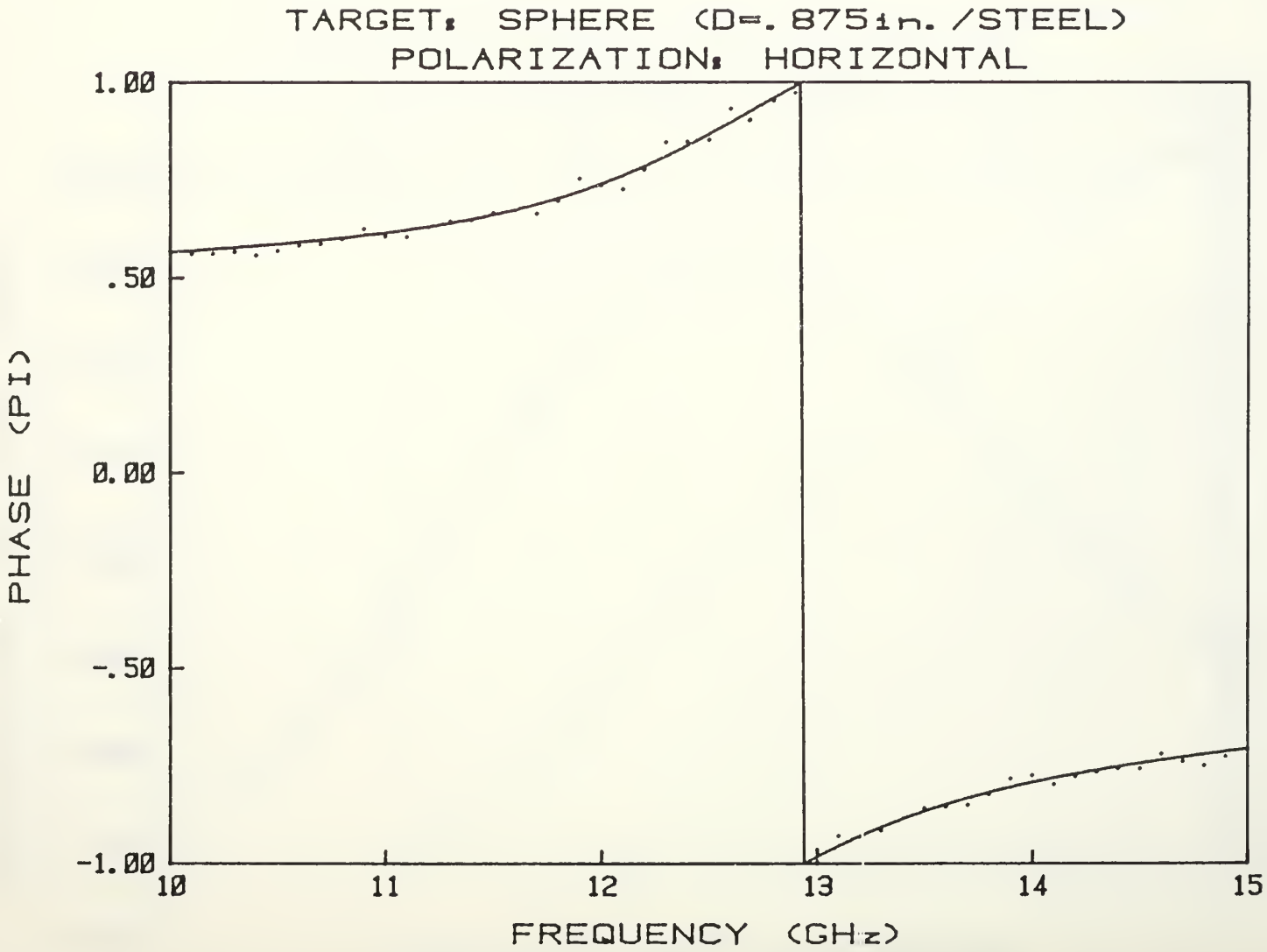

Figure 3.16 TARGET1 - Phase

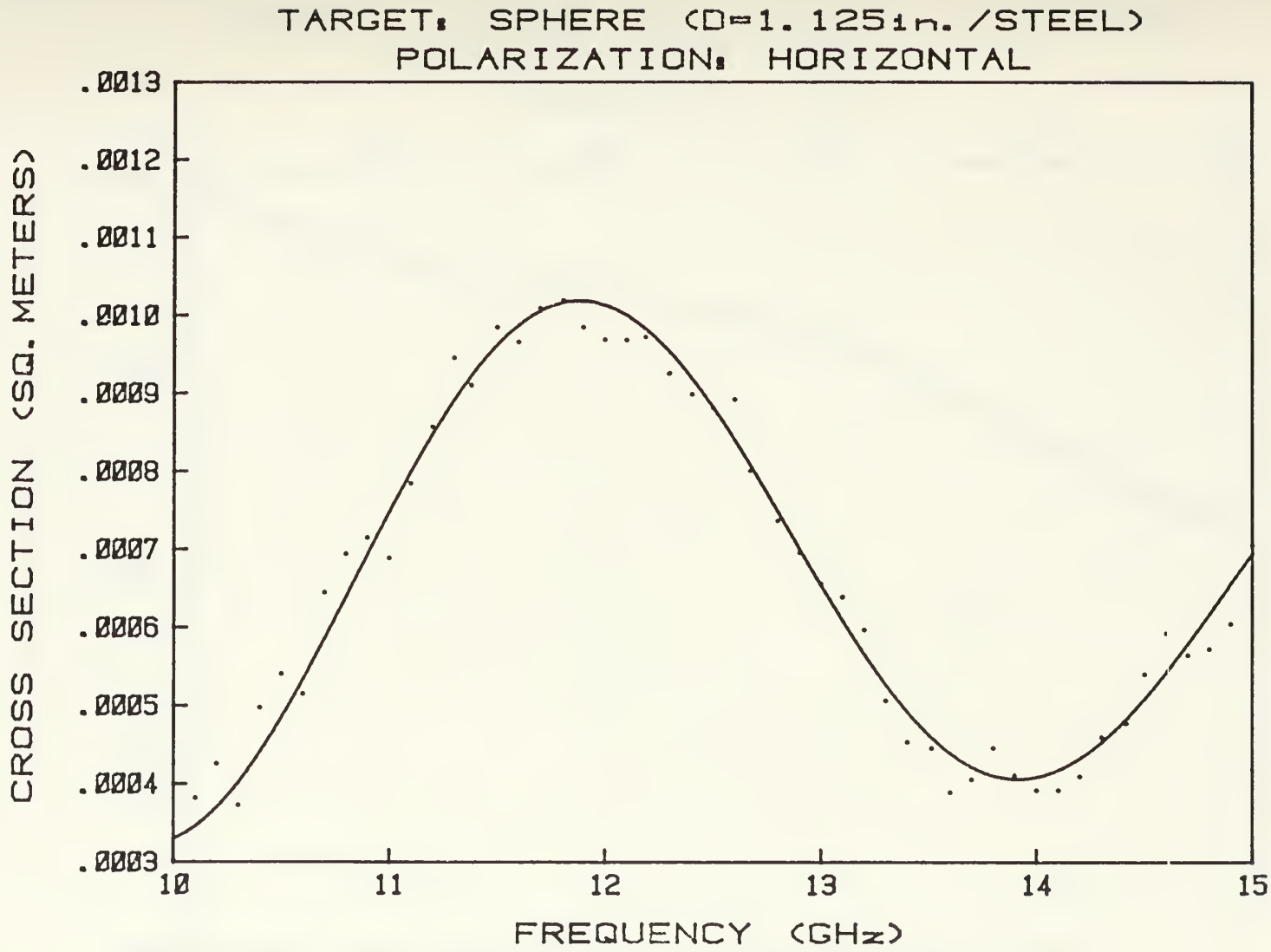

Figure 3.17 TARGET2 - Cross Section

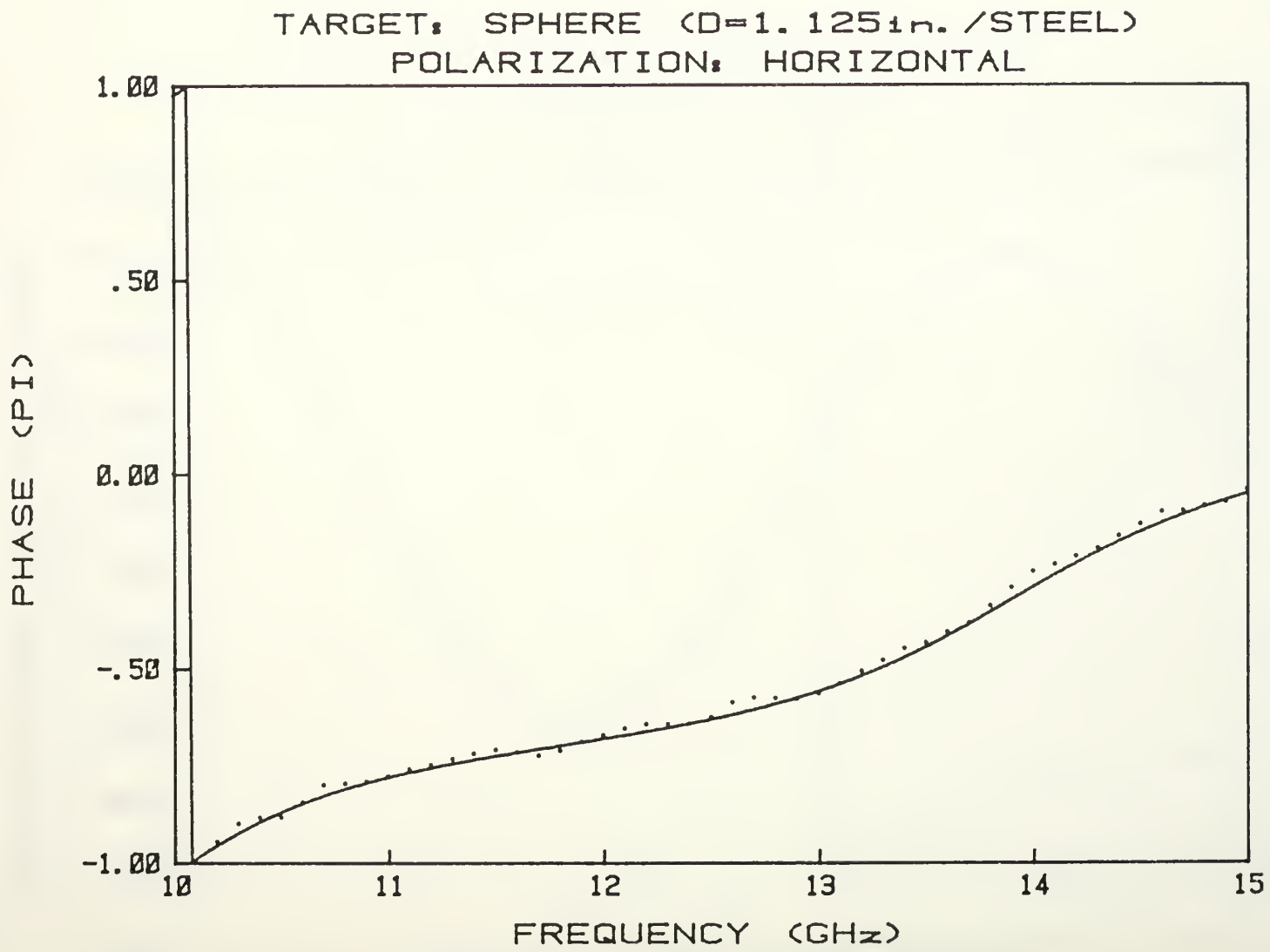

Figure 3.18 TARGET2 - Phase

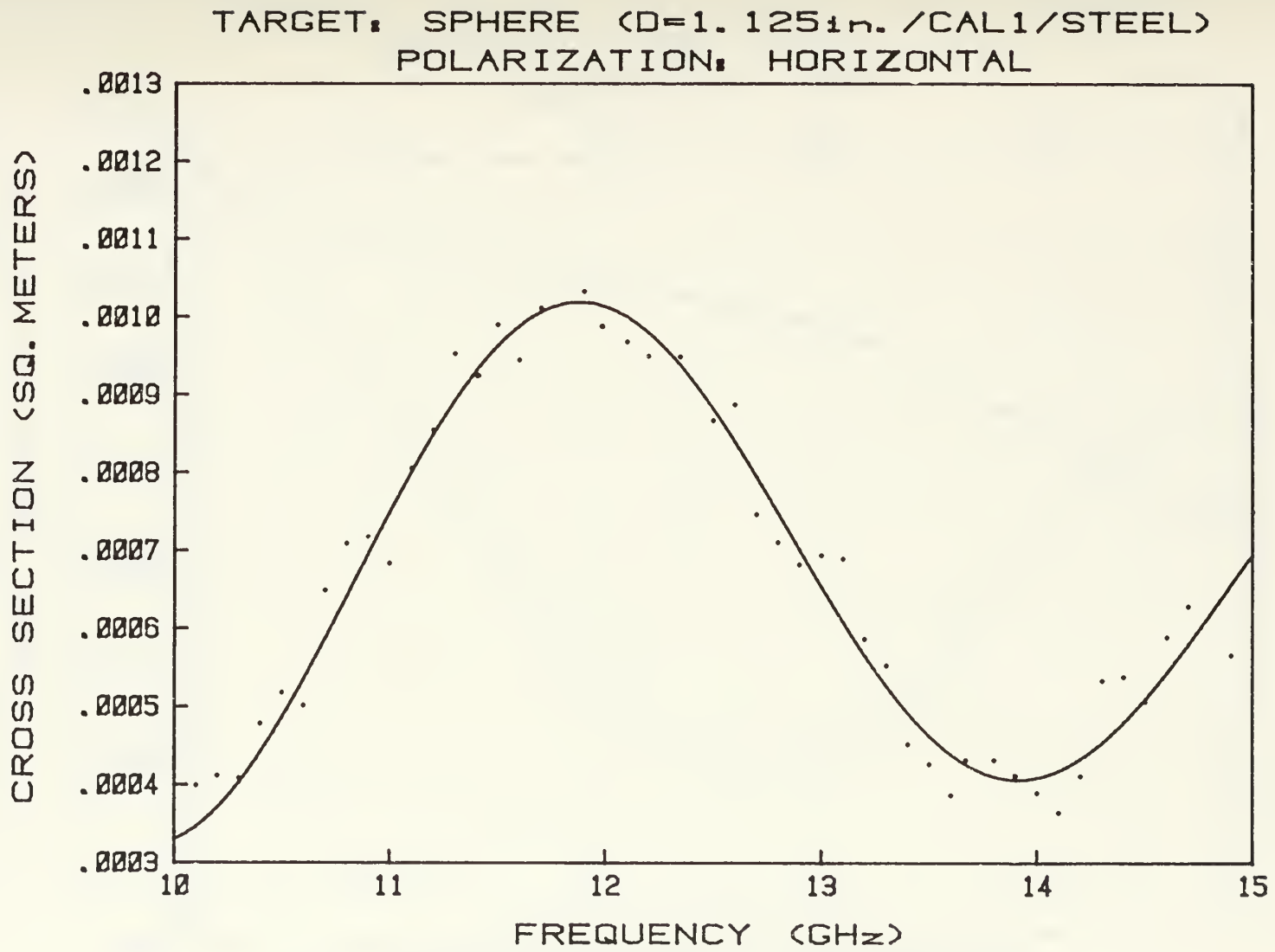

Figure 3.19 TARGET2 - Cross Section

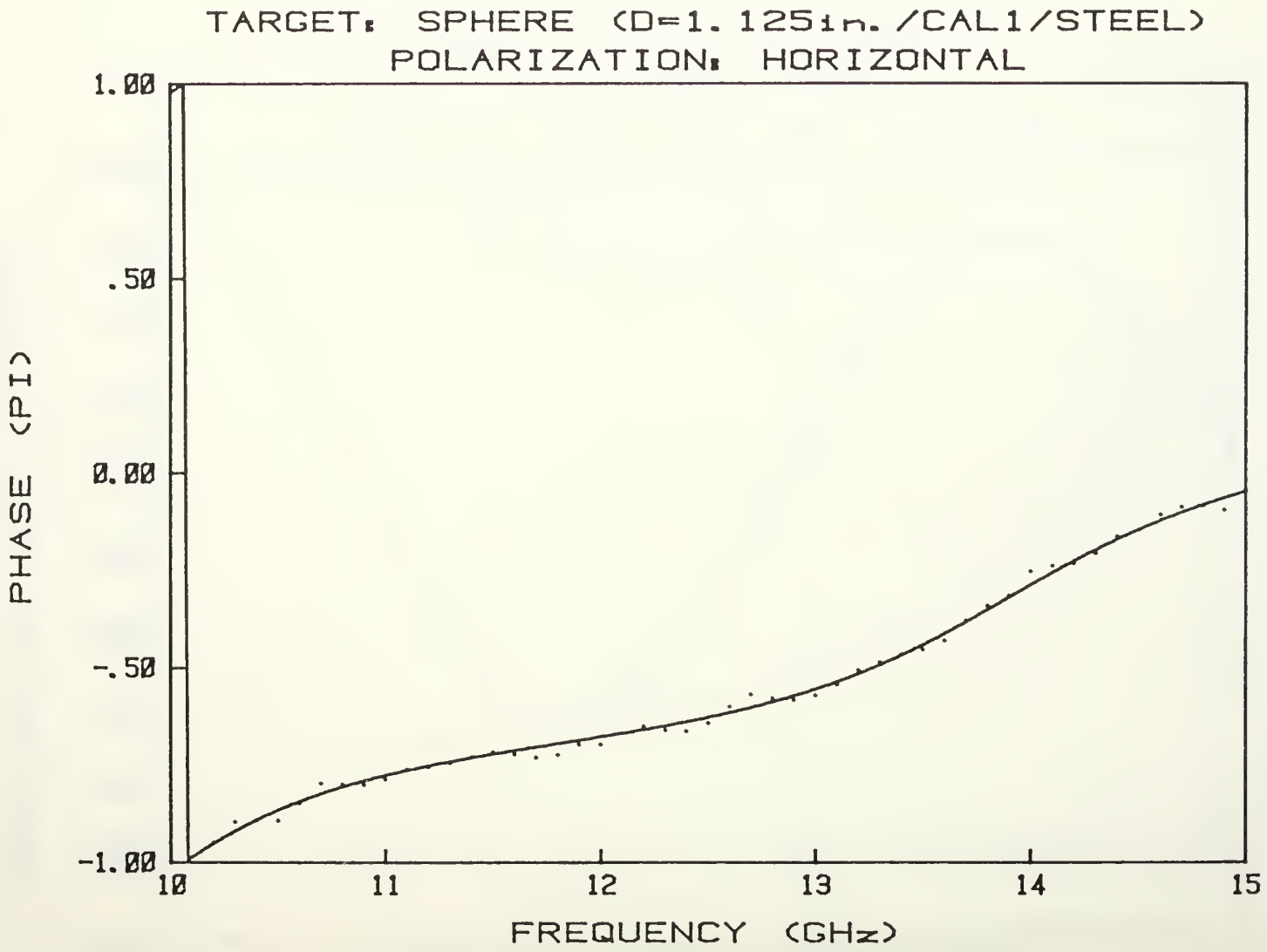

Figure 3.20 TARGET2 - Phase

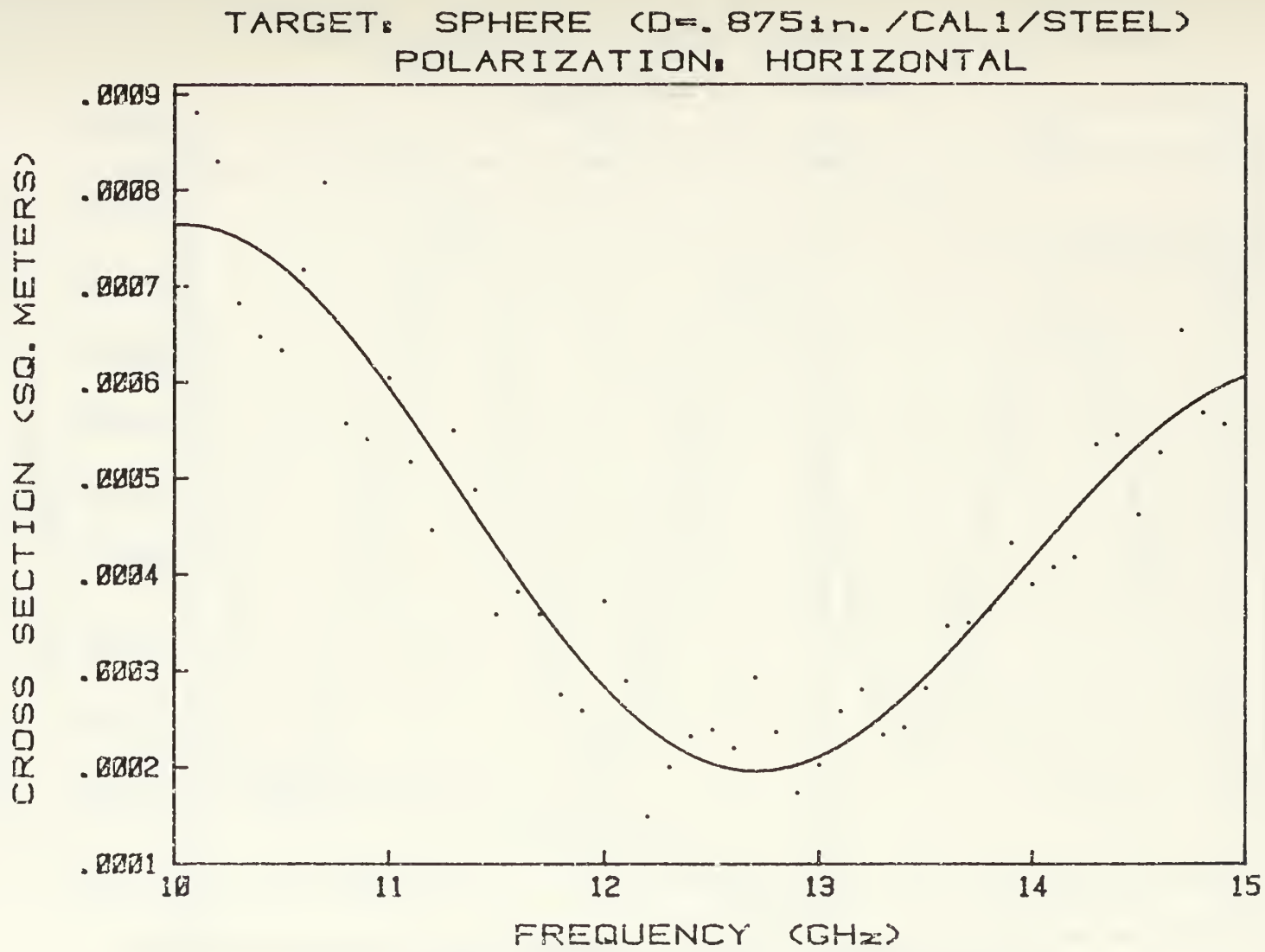

Figure 3.21 TARGET1 - Cross Section

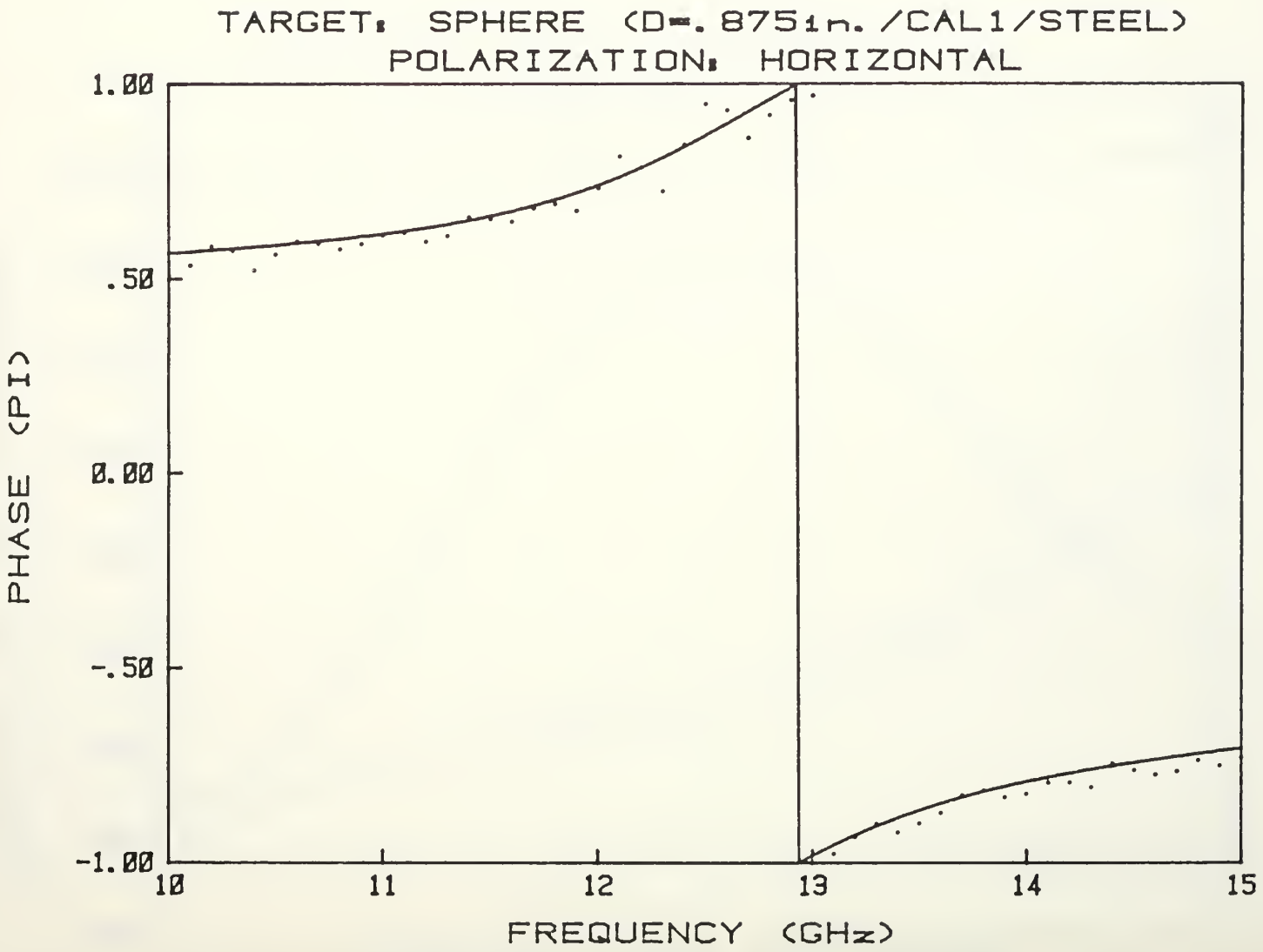

Figure 3.22 TARGET1 - Phase

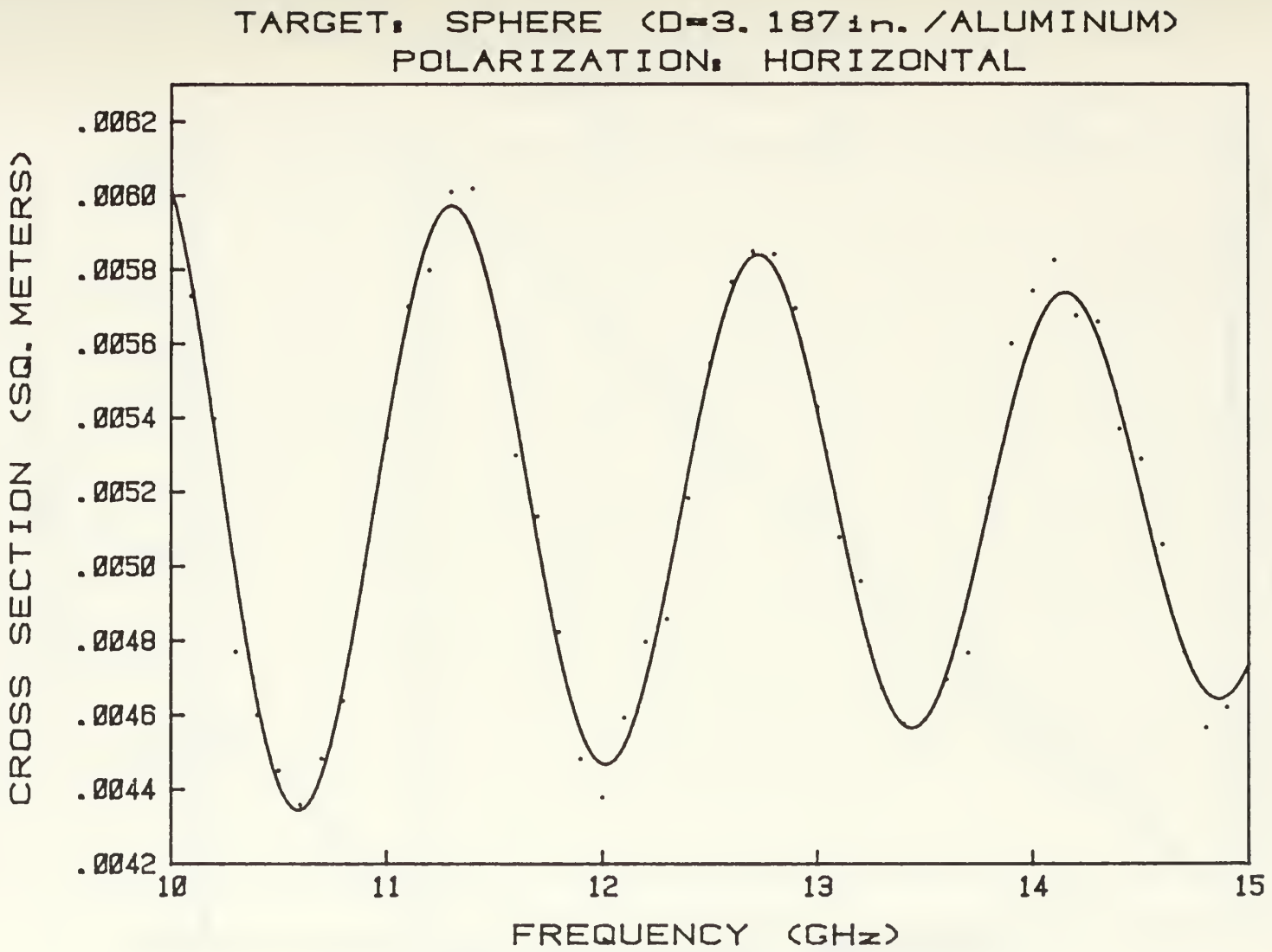

Figure 3.23 TARGET3 - Cross Section

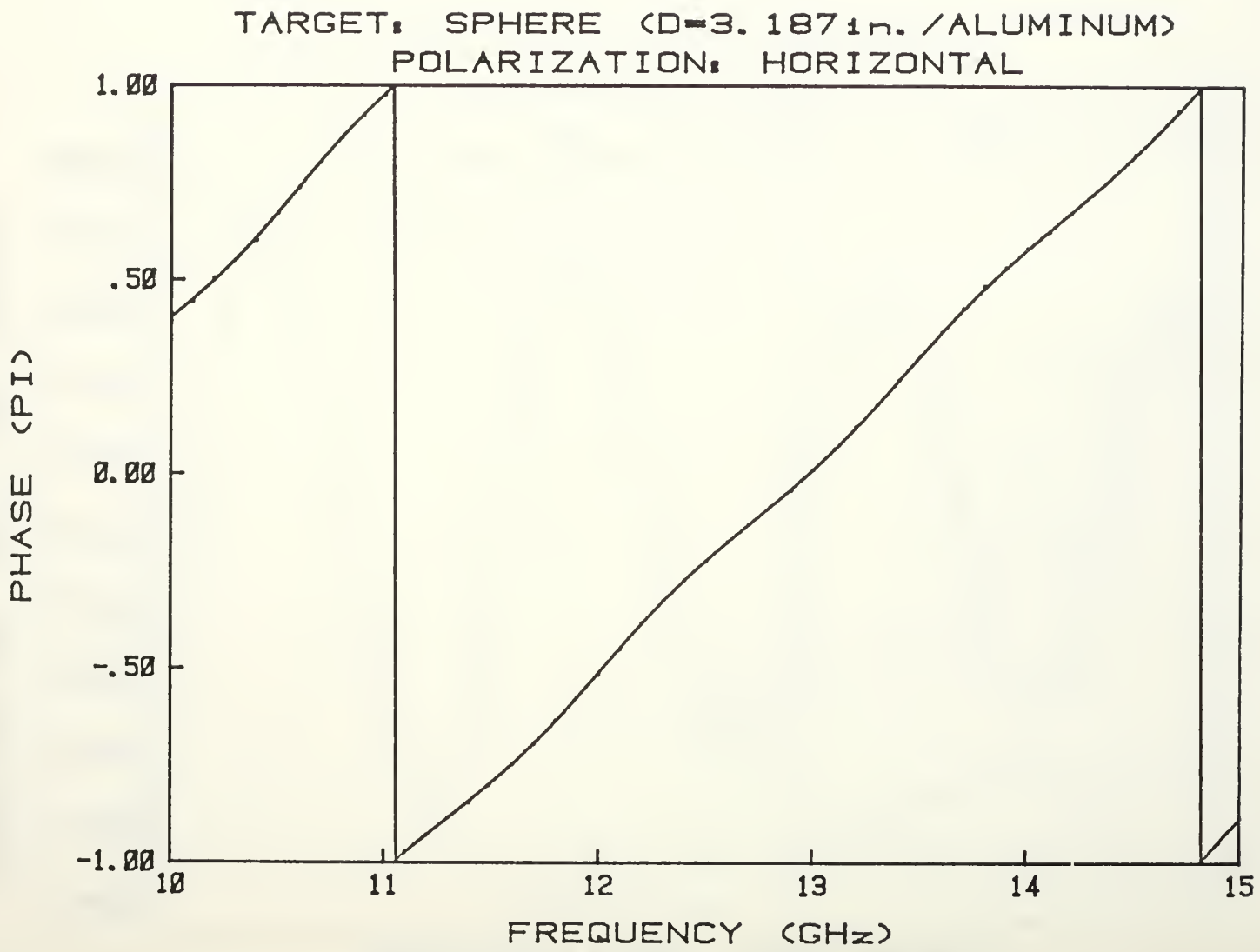

Figure 3.24 TARGET3 - Phase

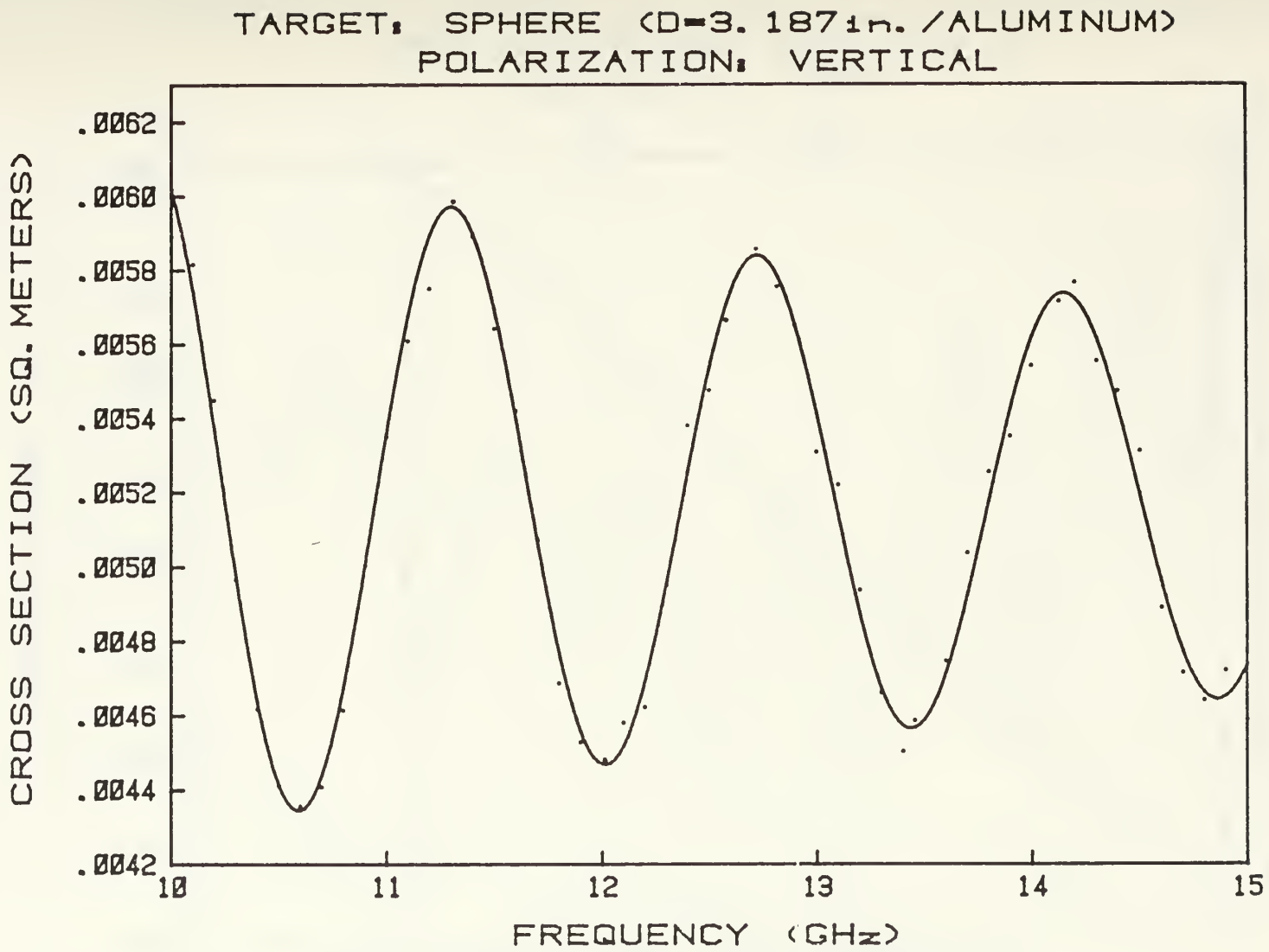

Figure 3.25 TARGET3 - Cross Section

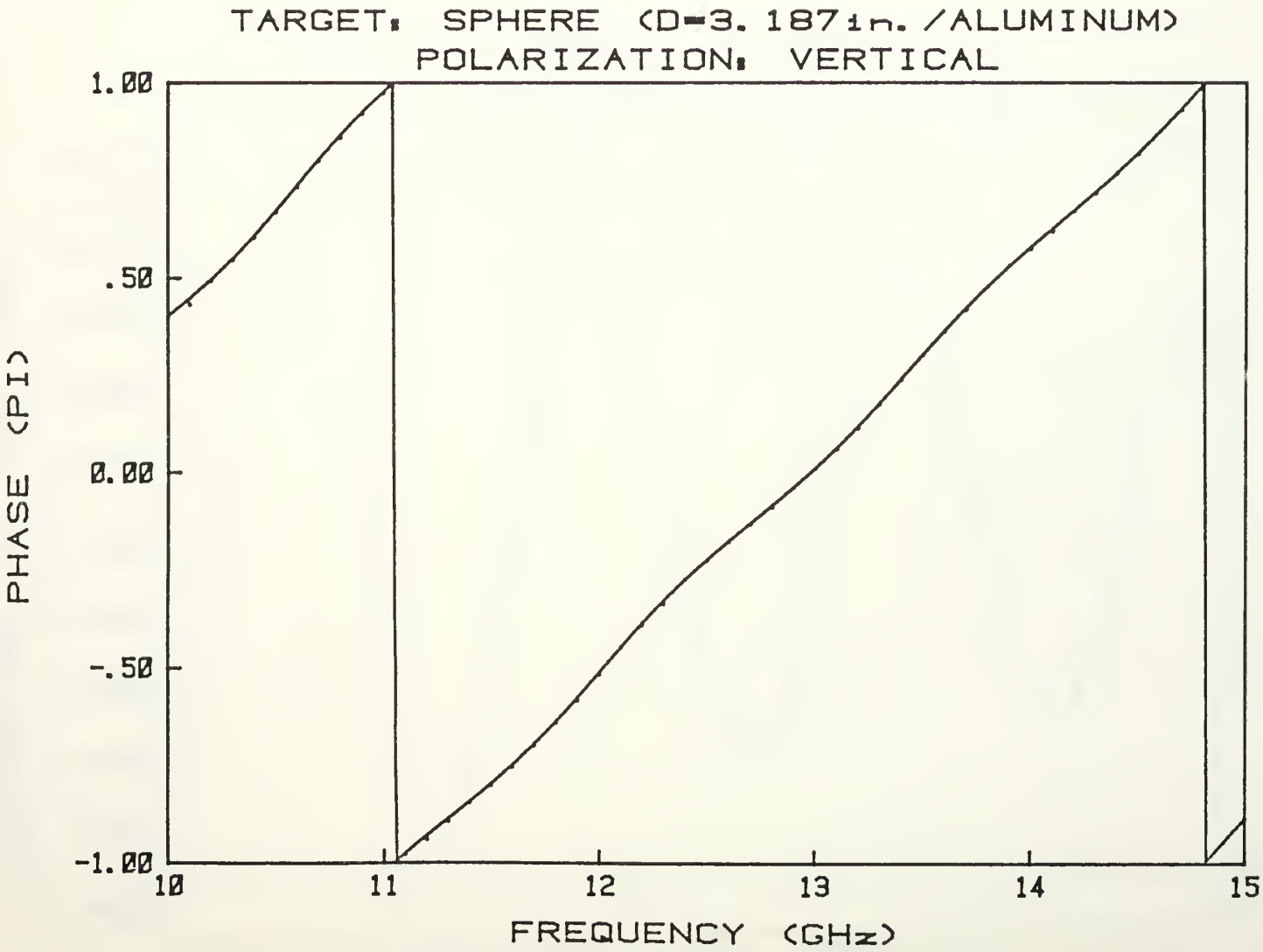

Figure 3.26 TARGET3 - Phase

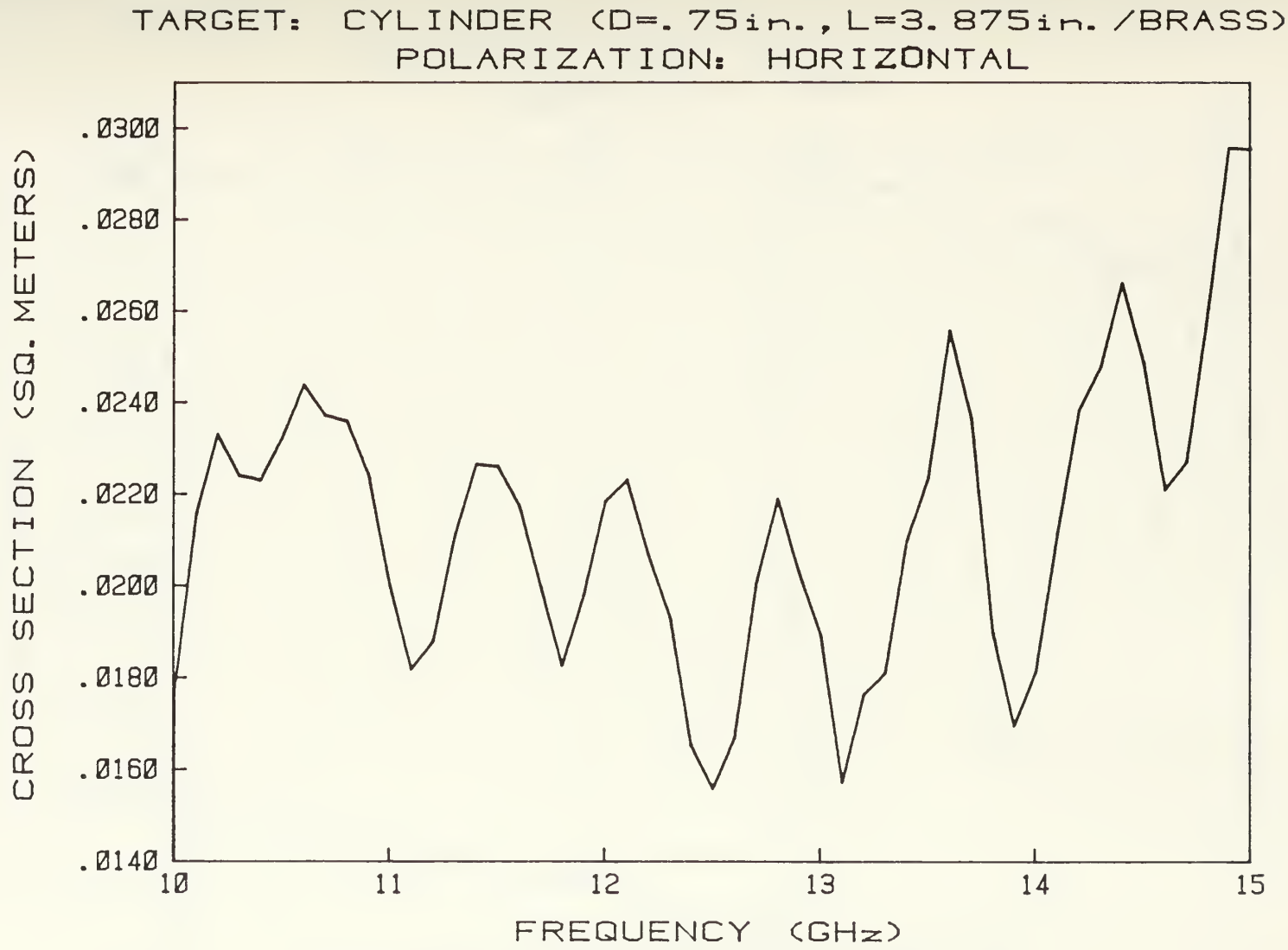

Figure 3.27 TARGET4 - Cross Section

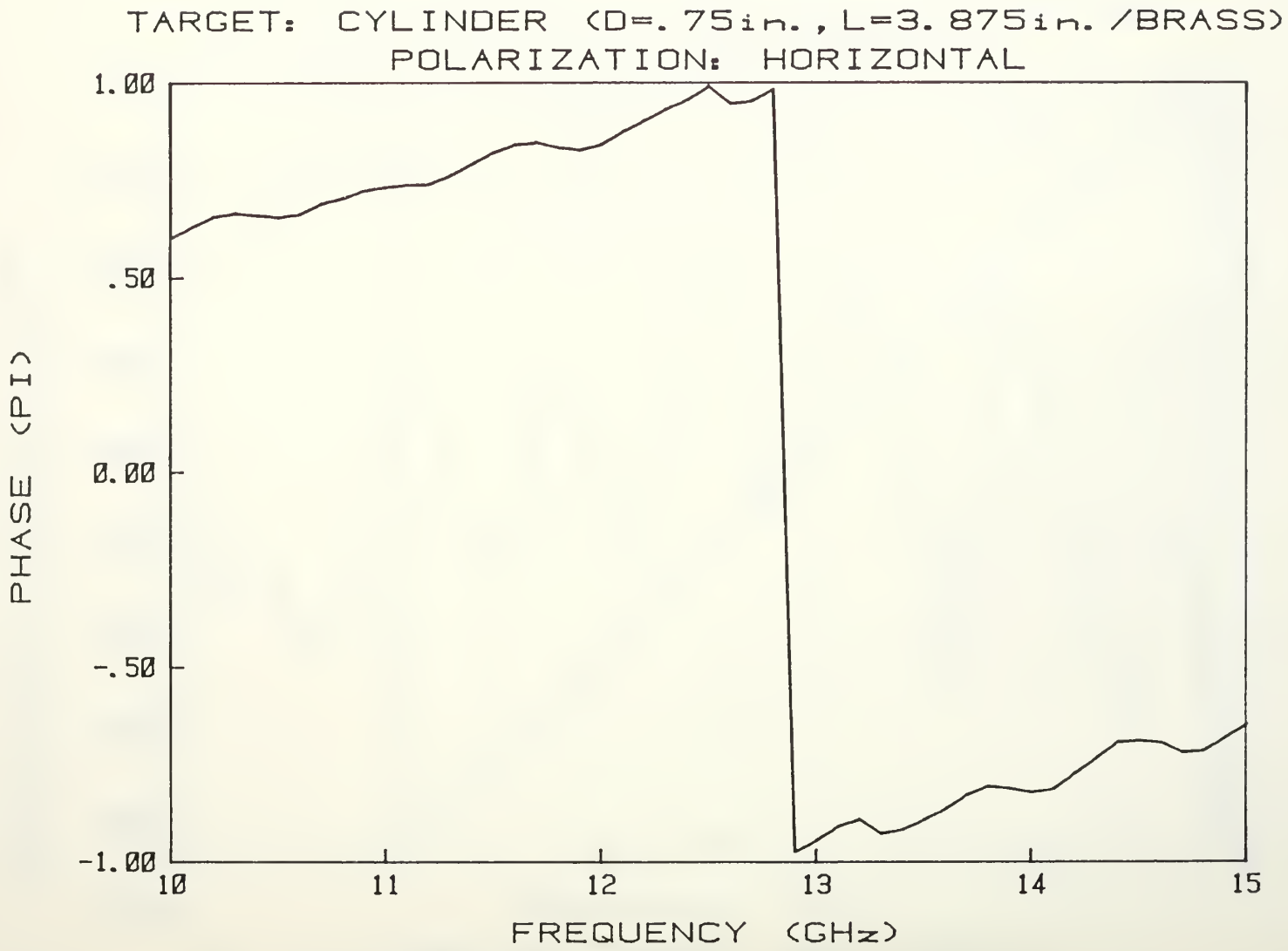

Figure 3.28 TARGET4 - Phase

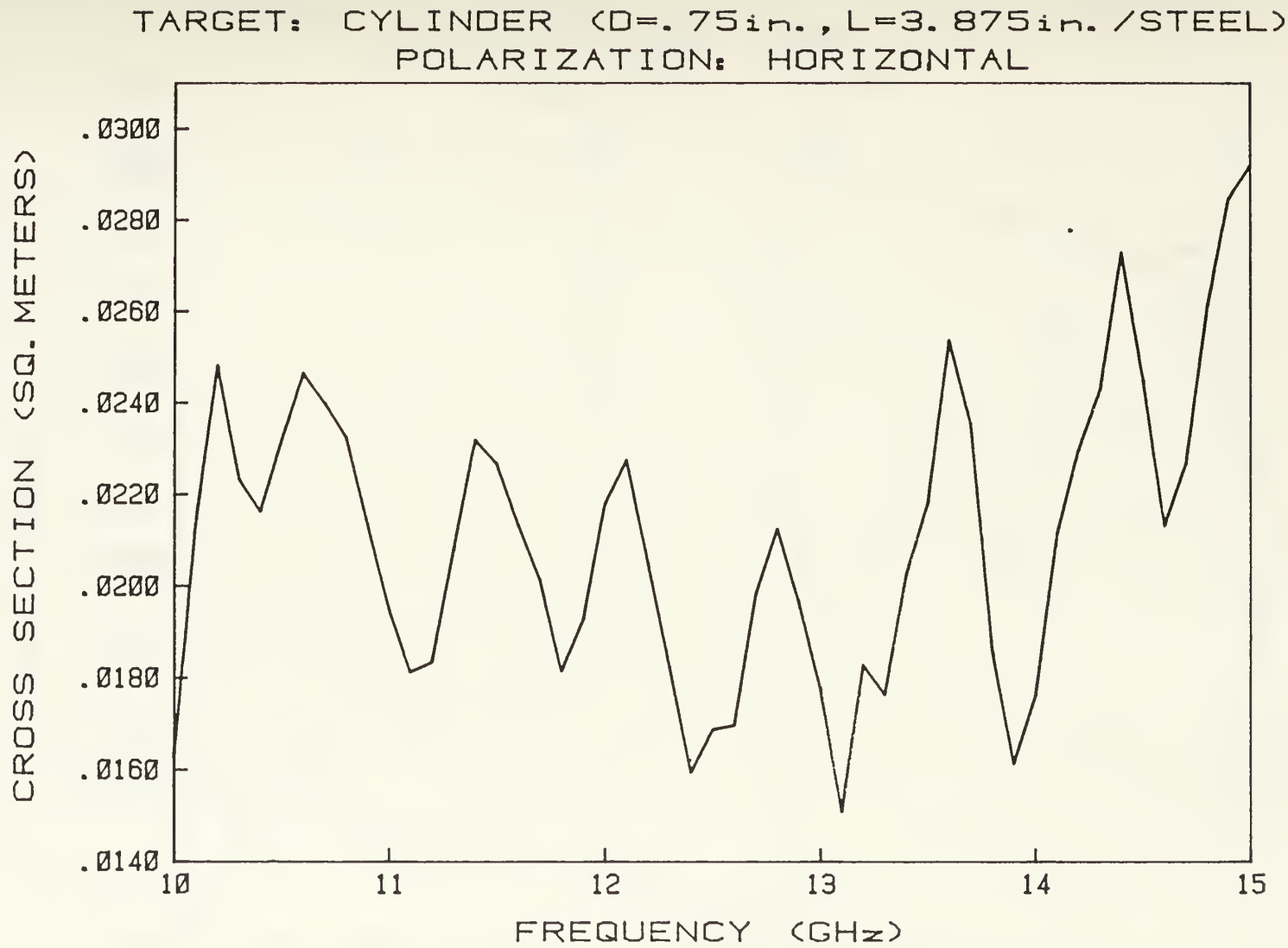

Figure 3.29 TARGET5 - Cross Section

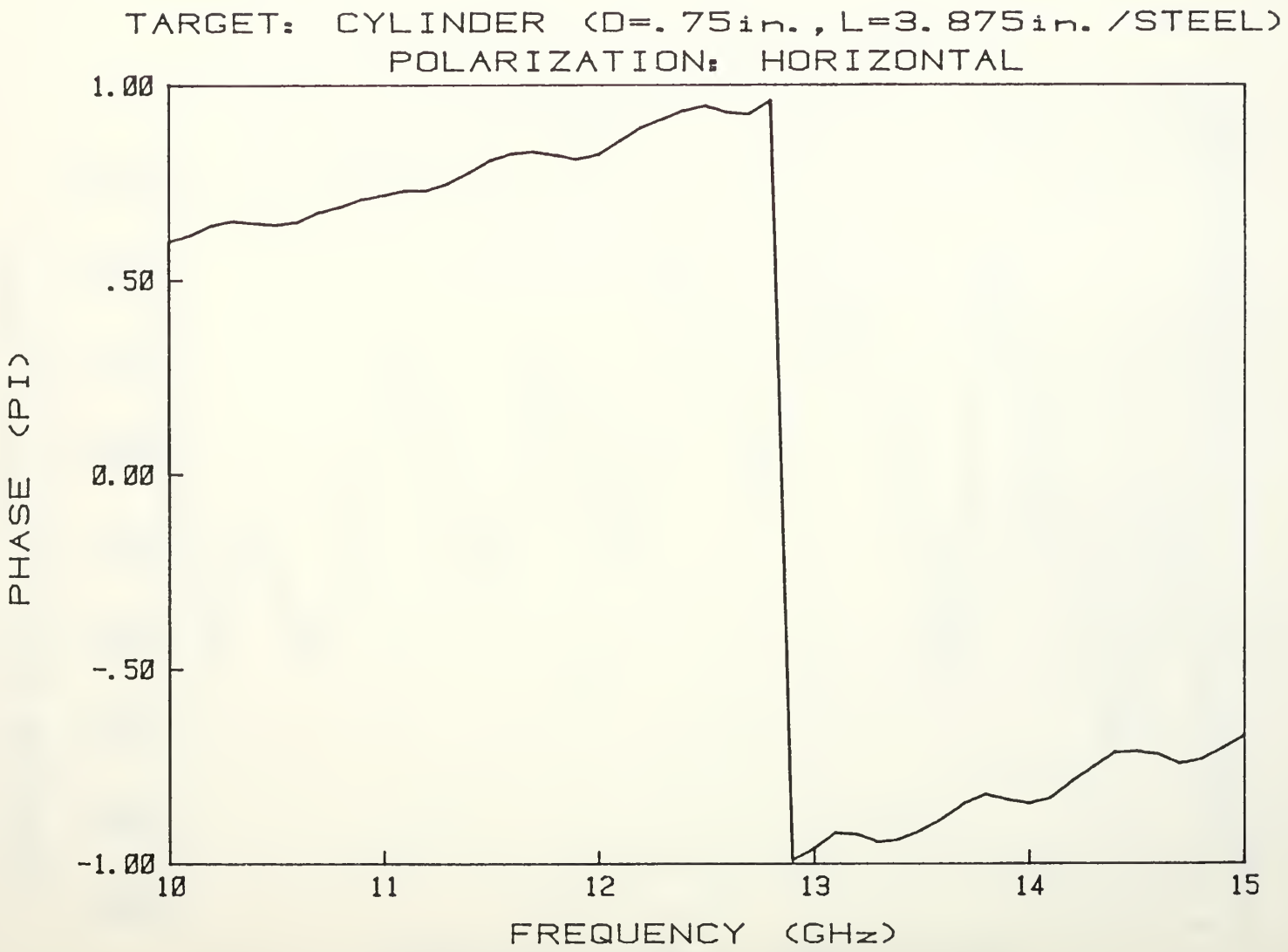

Figure 3.30 TARGET5 - Phase

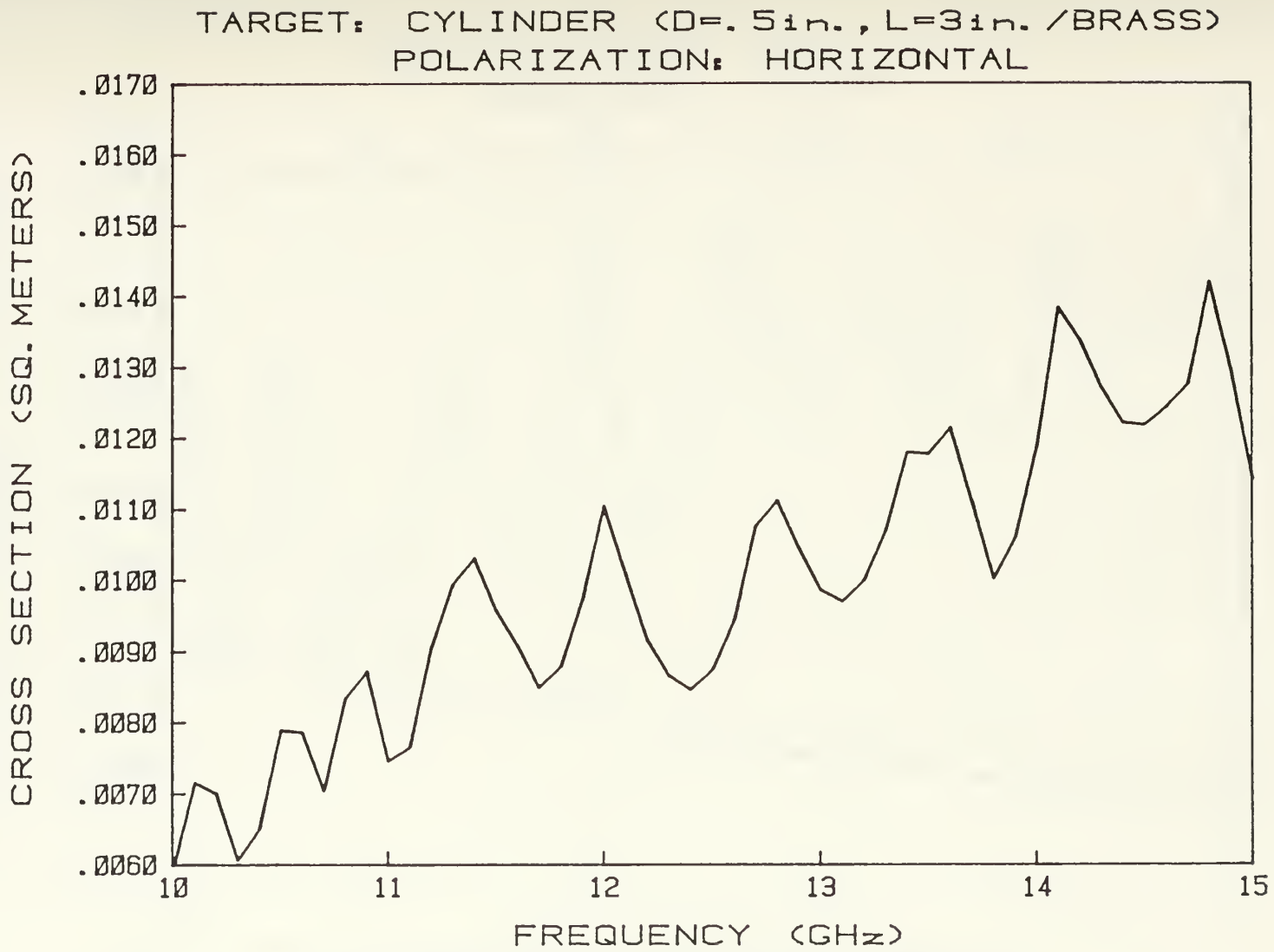

Figure 3.31 TARGET6 - Cross Section

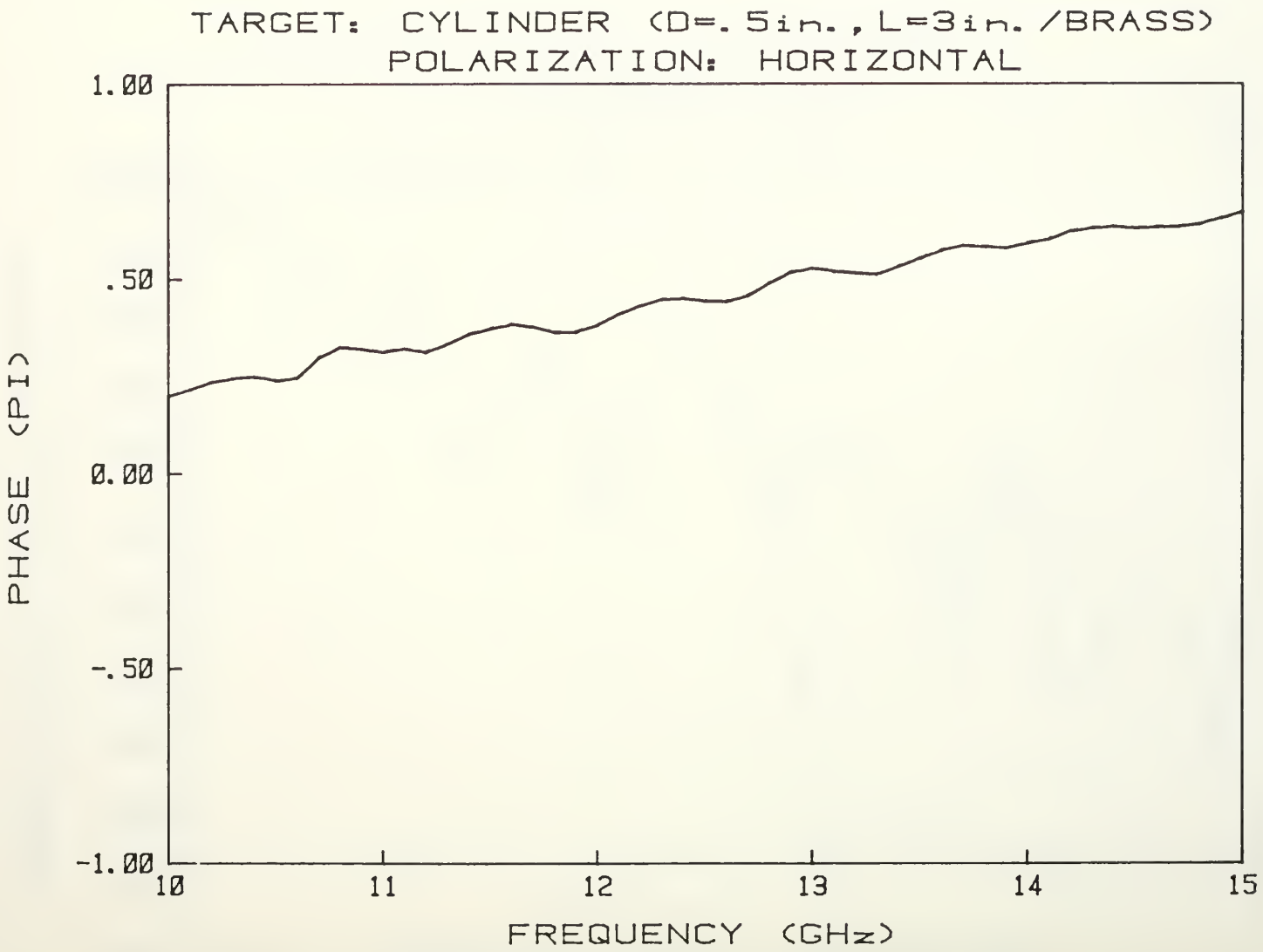

Figure 3.32 TARGET6 - Phase

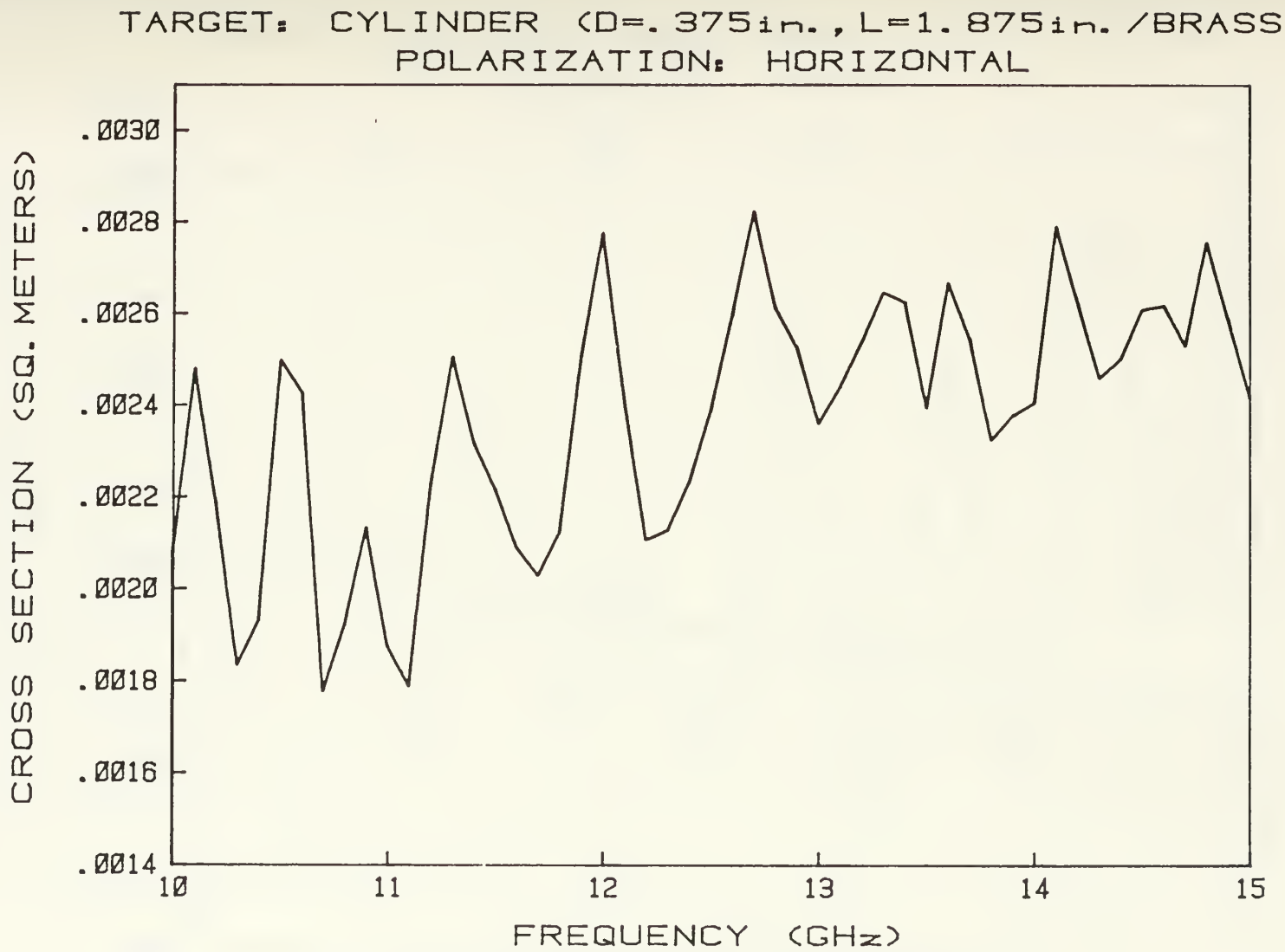

Figure 3.33 TARGET7 - Cross Section

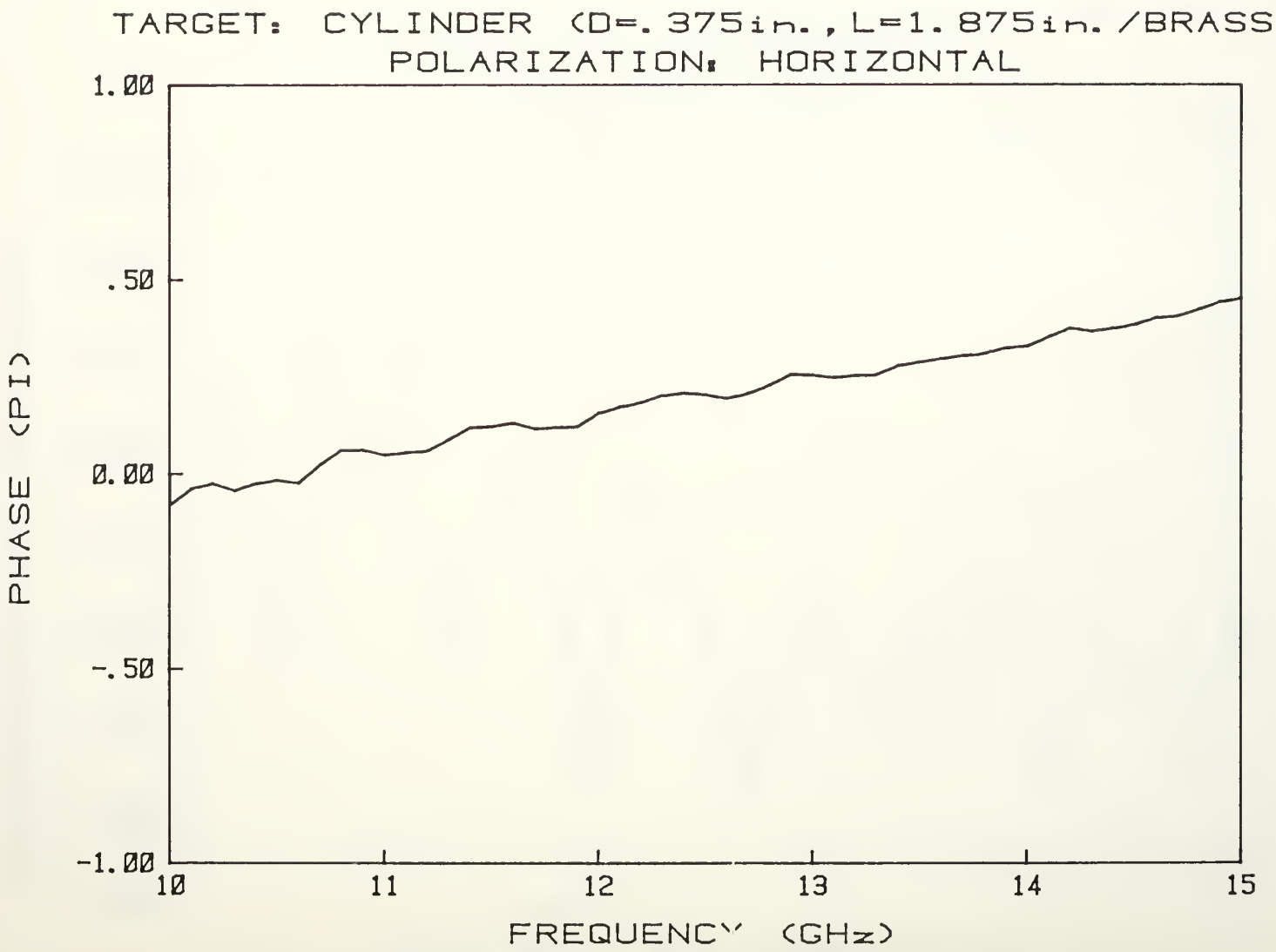

Figure 3.34 TARGET7 - Phase

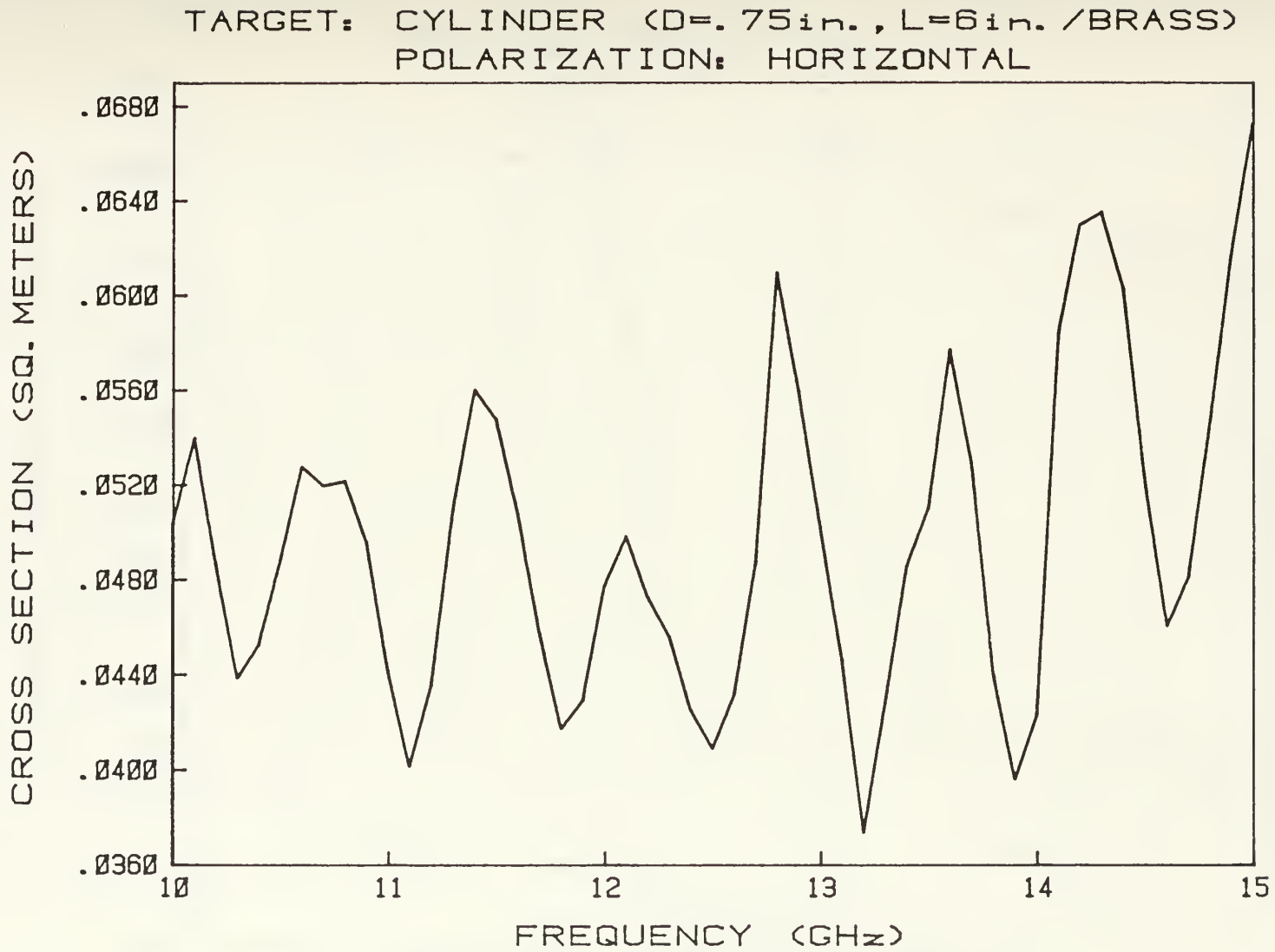

Figure 3.35 TARGET8 - Cross Section

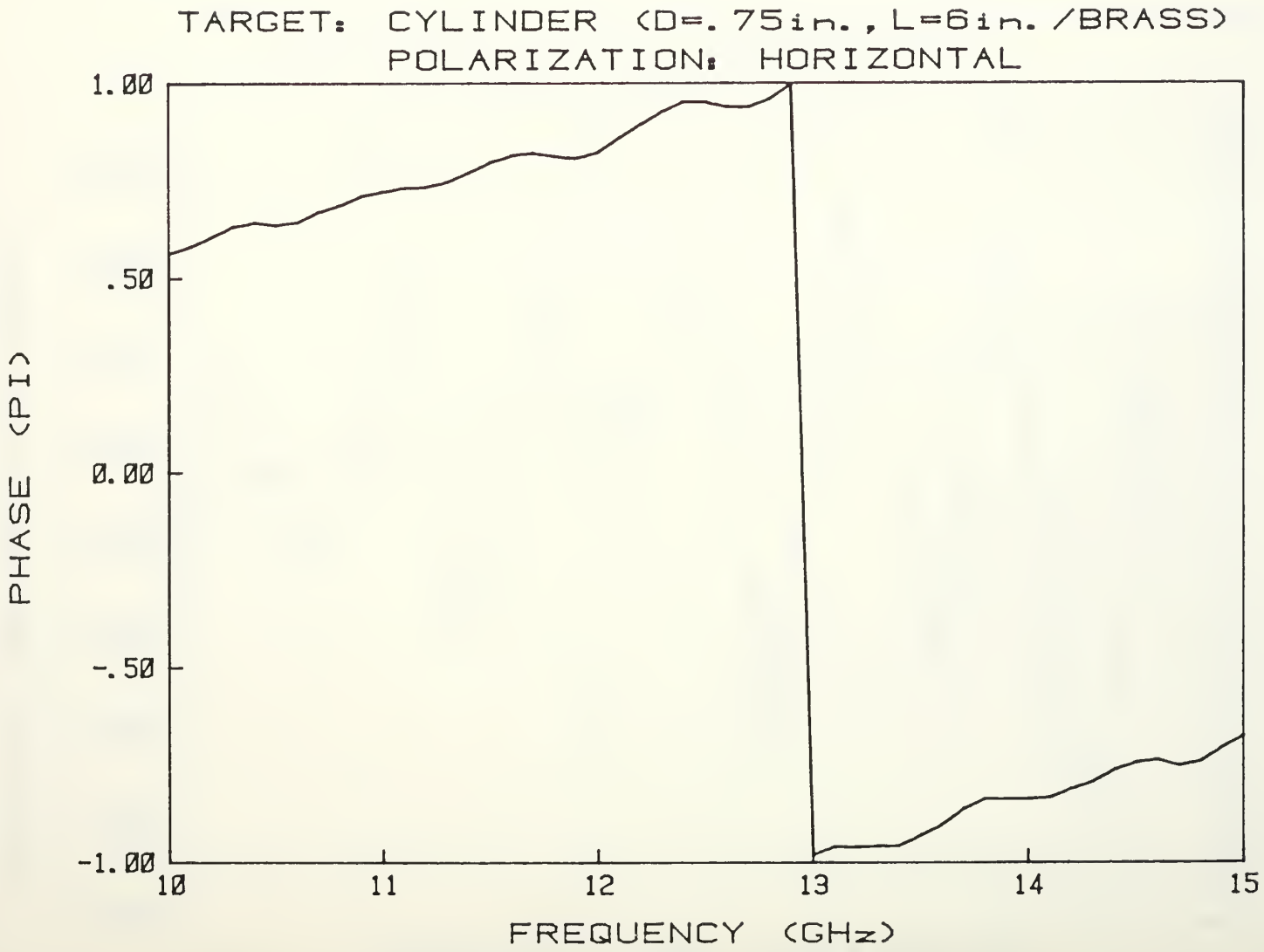

Figure 3.36 TARGET8 - Phase

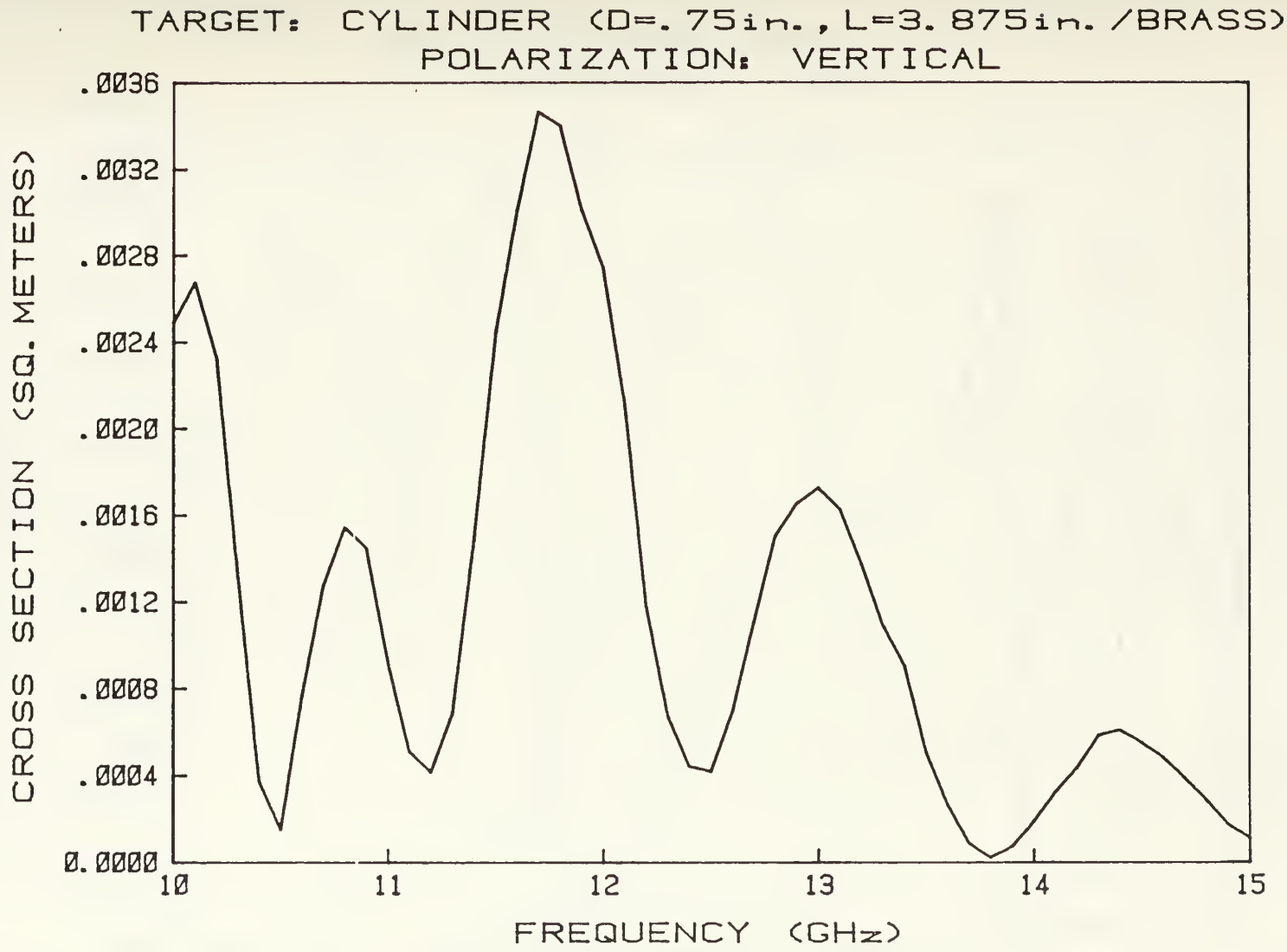

Figure 3.37 TARGET4 - Cross Section

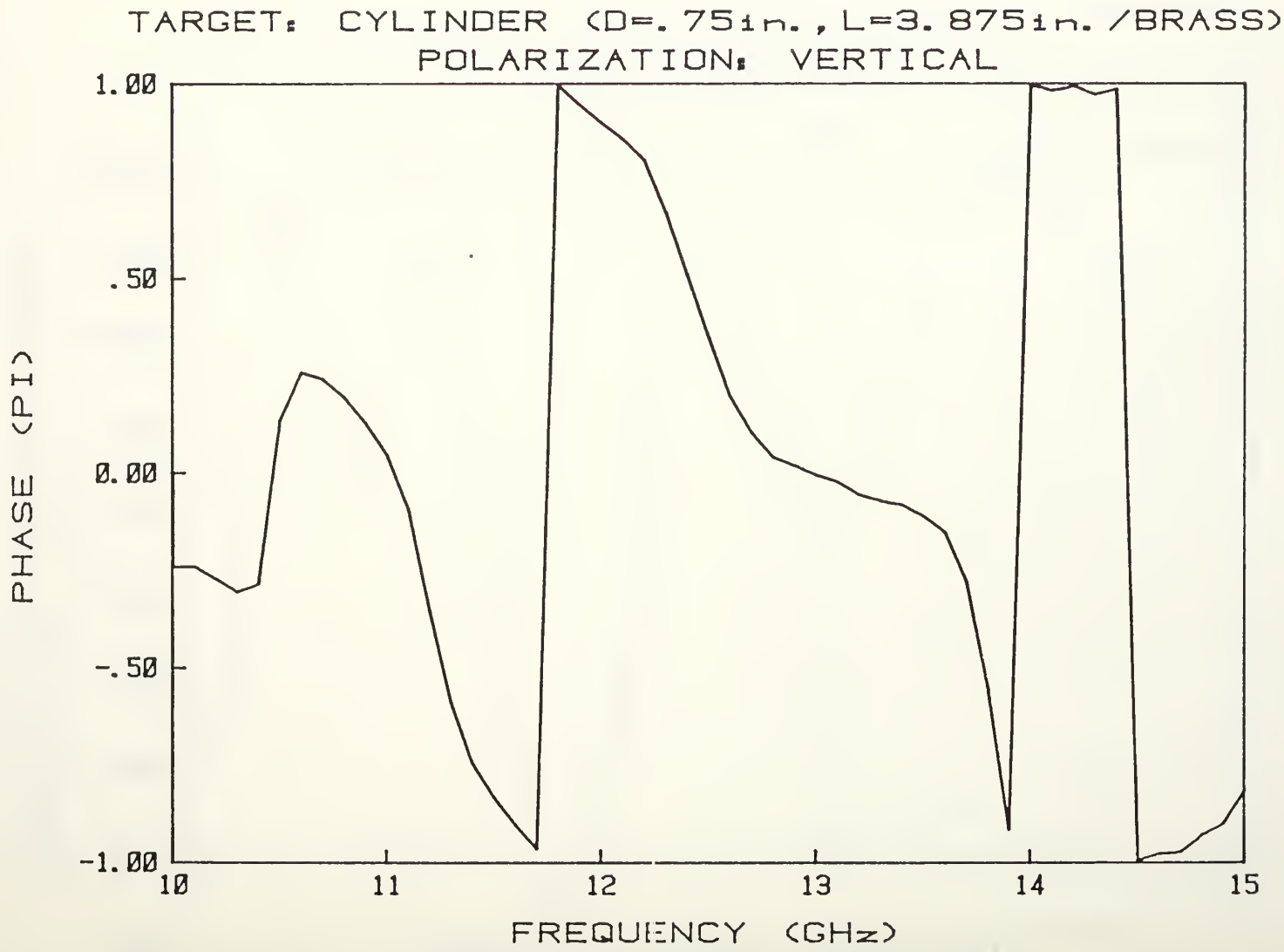

Figure 3.38 TARGET4 - Phase

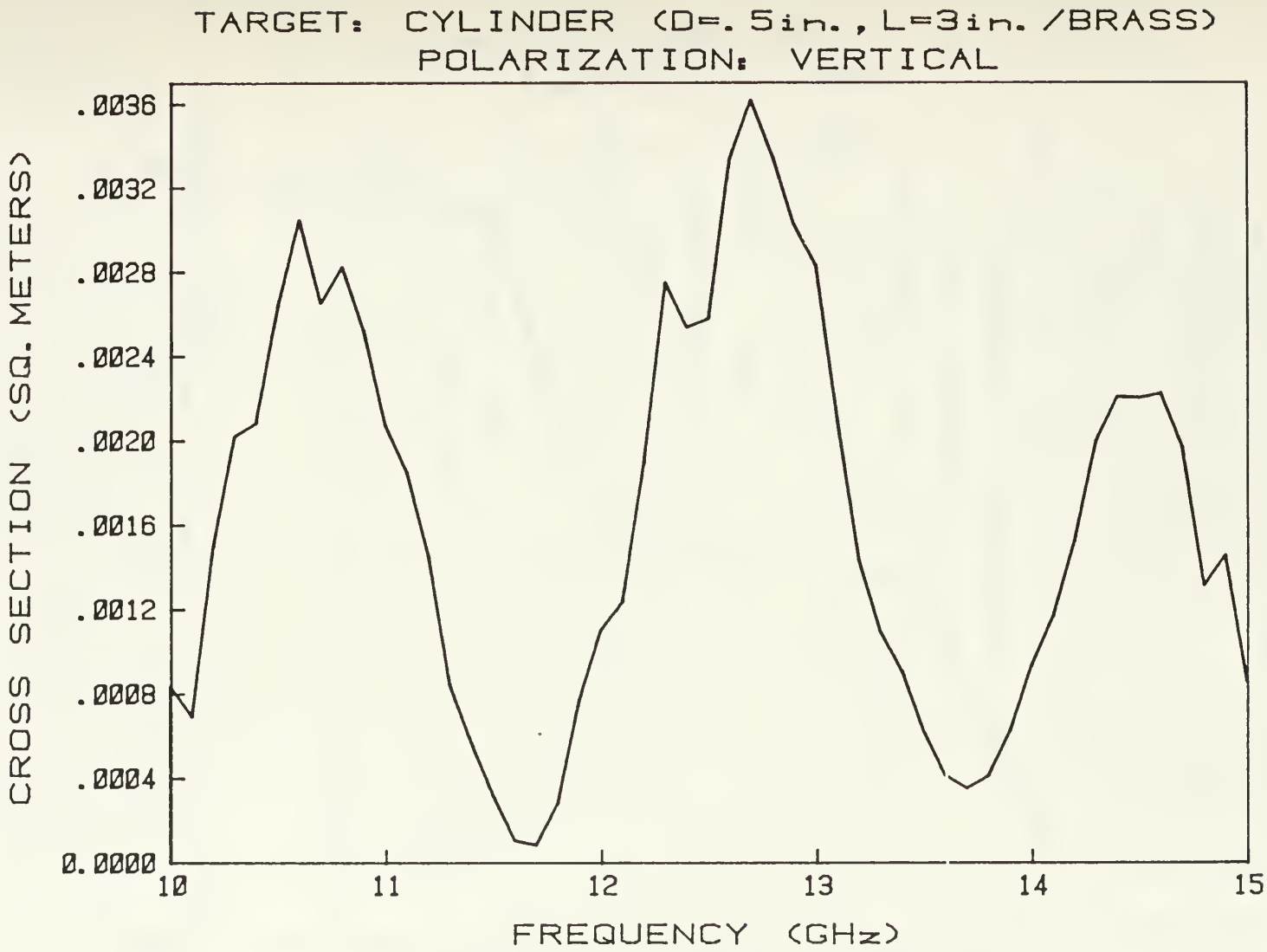

Figure 3.39 TARGET6 - Cross Section

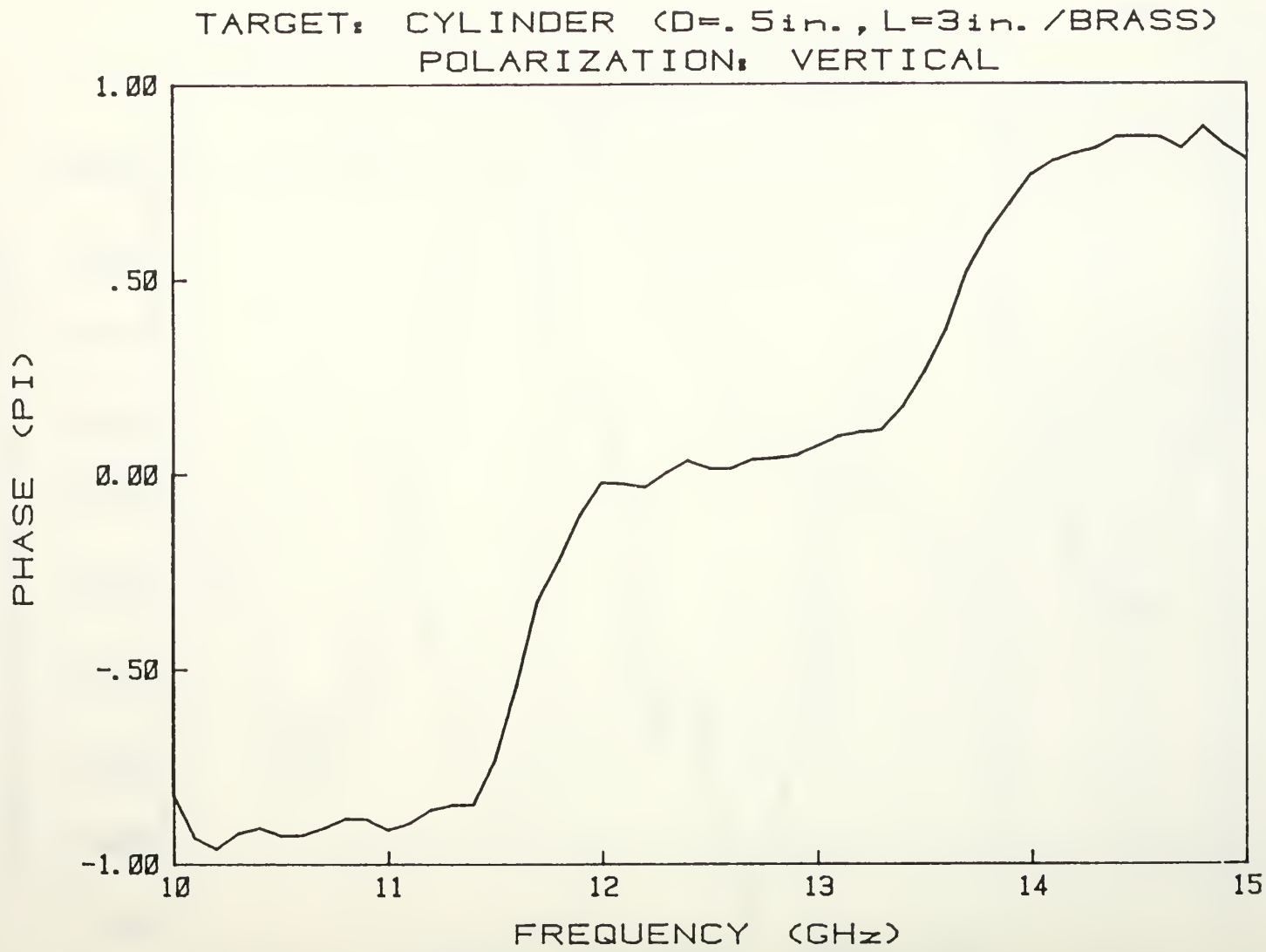

Figure 3.40 TARGET6 - Phase

IV. DESCRIPTION OF COMPUTER PROGRAMS

The computer programs described in this chapter are written in BASIC, for frequency domain scattering measurements at the Naval Postgraduate School. They are run on the Hewlet Packard - 85 microcomputer which, along with HP 82901M Flexible Disc Drive and HP 7225B Plotter, controls programable instruments in experimental setup (Figure 3.1), performs necessary computations and store and plot results of the measurements. Four programs were written to complete scattering experiment. First, "SPHERE.DRIVE0" program computes theoretical values for perfectly conducting sphere which are latter used for system calibration by the program "CALIB.DRIVE0". When the calibration is completed and system transfer function obtained, program "TARGET.DRIVE0" serves for target data acquisition and computation of its back scattering cross section and phase shift, and to plot those results immediately after measurement completion. Measurement results can be stored in the files on floppy disc, and if we want them to plot without taking measurement again, it is convenient to use separate program "PLOT.DRIVE0". Programs are written to be interactive and user friendly. All that is necessary to run any of those programs is to load them into main memory and then issue the command "RUN".

A. THEORY OF SPHERE

This program, under the name "SPHERE.DRIVE0", computes theoretical values of the back scattering cross section and the phase shift of a perfectly conducting sphere, using Mie solution given by equations (2.17, 2.18). Theoretical values

are stored in files of 800 records, one for each frequency, in the frequency range from 2.02 GHz to 18 GHz, at 0.02 GHz steps. The main part of the program (lines 10 through 660) creates the file named "H$", that stores one value of the cross section and one value of the phase, for each frequency increment of 0.02 GHz. It calls in SUBROUTINE I (lines 710 through 990), and this subroutine by itself calls in SUBROUTINE II (lines 1040 through 1530), which together carry out the task of computation using previously mentioned equations (2.17, 2.18). Program is listed in following pages.

```
 10 ! "SPHERE.DRIVE0"
 20 !
 30 !
 40 ! PROGRAM TO COMPUTE
 50 ! VALUES OF BACKSCATTERING
 60 ! CROSS SECTION AND PHASE
 70 ! FOR A PERFECTLY
 80 ! CONDUCTING SPHERE.
 90 !
100 !
110 ! THEORETICAL VALUES ARE
120 ! STORED IN FILES OF 800
130 ! RECORDS, ONE FOR EACH
140 ! FREQUENCY FROM 2.02 GHZ
150 ! TO 18 GHZ AT .02 GHZ
160 ! STEPS.
170 !
180 !
190 ! "THEOR0.DRIVE1" FOR THE
200 ! .875" DIAMETER SPHERE
210 ! "THEOR1.DRIVE1" FOR THE
220 ! 1.125" DIAMETER SPHERE
230 ! "THEOR3 DRIVE1" FOR THE
240 ! 3.187" DIAMETER SPHERE
250 !
260 !
270 !
280 ! FILE H$ STORES THE
290 !  COMPUTED RESULT
300 !
310 H$="THEOR1.DRIVE1"
320 !
330 A0=1.125*.0254/2 ! SPHERE
        RADIUS IN METERS
340 !
350 !
360 X9=2*PI ! PARAMETER
370 !
380 !
390 Q1=2 ! STARTING FREQ IN GHZ
400 Q2=18 ! FINAL FREQ IN GHZ
410 Q4=.02 ! FREQ STEP IN GHZ
420 ON ERROR GOTO 440
430 PURGE H$
440 OFF ERROR
450 CREATE H$,800,16 ! OPEN A
    NEW FILE WITH 800 RECORDS
460 ! OF 16 BYTES EACH. EVERY
470 ! RECORD STRORES ONE MAGNI
      TUDE AND ONE PHASE DATA.
480 !
490 ASSIGN# 1 TO H$
500 DIM B8(144),B9(144),D8(144),
    D9(144) ! 144>L0=INT(2*K0*A0
    +3)
510 F0=Q1
520 FOR I=1 TO 800
```

```
530 DISP "FREQ LOOP=",I
540 F0=F0+Q4
550 DISP "FREQ (GHZ)=",F0
560 K1=.3/F0 ! WAVELENGTH
570 K0=X9/K1 ! WAVE NUMBER
580 GOSUB 700
590 DISP "E =",E0
600 DISP "P =",P0
610 PRINT# 1,I ; E0,P0
620 NEXT I
630 ASSIGN# 1 TO *
640 CLEAR
650 DISP "END OF COMPUTATION"
660 END
670 !
680 !
690 !
700 !
710 ! SUBROUTINE I
720 !
730 L0=INT(2*K0*A0+3)
740 IF L0<145 THEN 760
750 DISP "K0*A0 TOO LARGE FOR
    CURRENT ARRAY DIM"
760 Z=K0*A0
770 GOSUB 1000
780 E8=0
790 E9=0
800 FOR N=1 TO L0
810 L=L0-N+1
820 M8=D8(L)^2+D9(L)^2
830 M9=B8(L)^2+B9(L)^2
840 A7=(L+.5)/M8/M9
850 A8=A7*(B9(L)*D9(L)-B8(L)*D8(
    L))
860 A9=A7*(B8(L)*D9(L)+B9(L)*D8(
    L))
870 E8=A8-E8
880 E9=A9-E9
890 NEXT N
900 E8=-E8
910 E9=-E9
920 E0=E8^2+E9^2
930 P0=ATN2(E9,E8)
940 E0=E0/K0*2*K1 ! CROSS-SECT.

950 P0=P0-X9*INT(P0/X9)
960 IF P0<PI THEN 980
970 P0=P0-X9
980 P0=-P0
990 RETURN
1000 !
1010 !
1020 !
1030 !
1040 ! SUBROUTINE II
1050 !
```

```
1060 IF Z>L0-1 THEN 1370
1070 Z2=Z^2/2
1080 N2=2*Z2+L0+1
1090 D1=2*N2+3
1100 D2=D1*(2*N2+5)
1110 D3=D2*(2*N2+7)
1120 D4=D3*(2*N2+9)
1130 F1=1-Z2/D1+Z2^2/(2*D2)-Z2^3
     /(6*D3)
1140 F2=Z*(1/D1-Z2/D2+Z2^2/(2*D3
     )-Z2^3/(6*D4))
1150 M=2*Z2
1160 S1=F1
1170 F1=(2*M+1)*F1/Z-F2
1180 F2=S1
1190 IF ABS(F1)<1.E100 THEN 1230
1200 F1=F1*1.E-100
1210 F2=F2*1.E-100
1220 S1=S1*1.E-100
1230 M=M-1
1240 IF M+1>L0 THEN 1160
1250 B8(L0)=F2
1260 B8(L0-1)=F1
1270 N0=L0-2
1280 FOR K=1 TO N0
1290 N=L0-K-1
1300 B8(N)=(2*N+3)*B8(N+1)/Z-B8(
     N+2)
1310 NEXT K
1320 A1=(SIN(Z)/Z-COS(Z))/B8(1)
1330 FOR K=1 TO L0
1340 B8(K)=A1*B8(K)
1350 NEXT K
1360 GOTO 1420
1370 B8(1)=SIN(Z)/Z-COS(Z)
1380 B8(2)=(3/Z^2-1)*SIN(Z)-3*CO
     S(Z)/Z
1390 FOR N=3 TO L0
1400 B8(N)=(2*N-1)*B8(N-1)/Z-B8(
     N-2)
1410 NEXT N
1420 B9(1)=-SIN(Z)-COS(Z)/Z
1430 B9(2)=(1-3/Z^2)*COS(Z)-3*SI
     N(Z)/Z
1440 FOR N=3 TO L0
1450 B9(N)=(2*N-1)*B9(N-1)/Z-B9(
     N-2)
1460 NEXT N
1470 D8(1)=(1-1/Z^2)*SIN(Z)+COS(
     Z)/Z
1480 D9(1)=(1/Z^2-1)*COS(Z)+SIN(
     Z)/Z
1490 FOR N=2 TO L0
1500 D8(N)=B8(N-1)-N*B8(N)/Z
1510 D9(N)=B9(N-1)-N*B9(N)/Z
1520 NEXT N
1530 RETURN
```

B. CALIBRATION PROGRAM

The calibration program "CALIB.DRIVE0" computes system transfer function using a perfectly conducting sphere (canonical target), over the frequency range of 10-15 GHz, at 0.1 GHz steps. Computation is based on theoretical values using the program "SPHERE.DRIVE", and the results are stored in the file "C$".

The main program (lines 10 through 1240) starts with comments and necessary declarations of the variables used (lines 10 through 520). Further, it takes theoretical values from H$ file and stores them into main memory. For the documentation of the results and user convenience, HEADER SUBROUTINE is called in (lines 2160 through 2280). To compute system transfer function, background data as well as the data acquired from canonical target must be available. The main program ofers two possibilities, whether to use the background data obtained in the most recent calibration, or to take them immediately after program is run. If user decides to take new background data, program remotes all devices establishing their initial setup (lines 530 through 870), and calls in BACKGROUND DATA COLLECTION SUBROUTINE. This subroutine serves to increment frequency of the signal generator (device 719) M1=51 times in steps of F9 =0.1 GHz, and in each loop to take averaged data of the magnitude and phase, acquired by the digital voltmeters. It computes their real and imaginary parts, to be stored in the file A$ as well (lines 1300 through 1490). To do so, it calls in SUBROUTINE TO ENTER MAGNITUDE AND PHASE DATA from digital voltmeters. HP 3456A digital voltmeter (device 720) reads magnitude, and HP 3455A digital voltmeter (device 722) reads phase (Figure 3.1). In each loop both digital voltmeters simultaneously take N0=10 readings of the magnitude and phase, average them and pass those values to the background data collection subroutine (lines 1550 through 1830).

The main program proceedes to compute canonical target data, after it is placed into anechoic chamber, by calling in TARGET DATA COLLECTION SUBROUTINE . This subroutine does exactly the same job the background data collection subroutine does. It calls in subroutine to enter magnitude and phase data from digital voltmeters. Results are then averaged, converted to real and imaginary parts and passed to the main program (lines 1890 through 2090). Having both background and target data, main program computes system transfer function (lines 1040 through 1240). That concludes calibration procedure. The program is listed bellow.

```
 10 ! "CALIB.DRIVE0"
 20 !
 30 !
 40 ! PROGRAM TO COMPUTE SYSTEM
 50 ! TRANSFER FUNCTION USING A
 60 ! PERFECTLY CONDUCTING
 70 ! SPHERE OVER 10-15 GHZ AT
 80 ! .1 GHZ STEPS. COMPUTATION
 90 ! BASED ON THE THEORETICAL
100 ! VALUES OBTAINED USING THE
110 ! PROGRAM "SPHERE.DRIVE0".
120 !
130 ! THE RESULTED SYSTEM TRANS-
140 ! FER FUNCTION IS STORED AS:
150 !
160 !
170 ! "CALIB0.DRIVE1" (0.875")
180 ! "CALIB1.DRIVE1" (1.125")
190 ! "CALIB3.DRIVE1" (3.187")
200 !
210 !
220 ! C$ IS THE FILE STORING
230 ! THE SYS. TRANSF. FUNCTION
240 !
250 ! H$ IS THE FILE STORING
260 ! THEORETICAL DATA
270 ! OF THE SPHERE
280 !
290 ! S$ DESCRIBES THE SPHERE
300 !
310 C$="CALIB3.DRIVE1"
320 H$="THEOR3.DRIVE1"
330 S$="3.187 INCH SPHERE"
340 A$="BKGRND.DRIVE1"
350 !
360 X9=2*PI ! A PARAMETER
370 !
380 OPTION BASE 1
390 N0=10 ! DIMENSION OF W()
400 F9=.1 ! FREQ. STEP IN GHZ
410 M1=51 ! M1=(U9-L9)/F9+2
420 L9=10 ! LOWER FREQ.IN GHZ
430 U9=15 ! UPPER FREQ.IN GHZ
440 DIM A(51,2) ! BACKGROUND
                  DATA
450 DIM B(51,2) ! TARGET
460 DIM G3(51,2) ! THEORY
470 ! CREATE C$,M1,16
480 ! CREATE A$,M1,16
490 ! STORE CALIBRATION DATA
      IN A FILE OF 51 RECORDS
500 ! EACH RECORD CONTAINS ONE
       MAGNITUDE AND ONE PHASE
510 ! DATA AT A FREQUENCY
520 !
530 ASSIGN# 1 TO H$
540 K0=(L9-2-F9)*50
```

```
550 FOR I=1 TO M1
560 K0=K0+50*F9
570 READ# 1,K0 ; G3(I,1),G3(I,2)
580 NEXT I
590 ASSIGN# 1 TO *
600 GOSUB 2160
610 DISP "DO YOU WANT TO USE THE
    MOST RECENT BACKGROUND DATA
              ?     Y/N "
620 INPUT P$
630 IF P$="N" THEN 680
640 ASSIGN# 4 TO A$
650 READ# 4 ; A(,)
660 ASSIGN# 4 TO *
670 GOTO 860
680 CLEAR
690 REMOTE 7 ! REMOTE ALL
                 DEVICES
700 CLEAR 7 ! CLEAR ALL DEVICES
710 OUTPUT 719 ;"P",L9,"Z1K0L3M0
    N601"
720 CLEAR
730 DISP "REMOVE TARGET FROM CHA
    MBER,PUSH 'CONT' WHEN READY"
740 LOCAL 7
750 BEEP @ BEEP
760 PAUSE
770 REMOTE 7
780 CLEAR
790 DISP "TAKING BACKGROUND DATA
    "
800 PRINT
810 ! PRINT "BACKGROUND DATA"
820 PRINT
830 OUTPUT 719 ;"P",L9,"Z1K0L3M0
    N601"
840 WAIT 200
850 GOSUB 1300
860 CLEAR
870 LOCAL 7
880 DISP "PUT TARGET INTO CHAMBE
    R,PUSH 'CONT' WHEN READY"
890 DISP "TARGET IS ",S$
900 BEEP @ BEEP
910 PAUSE
920 REMOTE 7
930 ASSIGN# 3 TO A$
940 PRINT# 3 ; A(,)
950 ASSIGN# 3 TO *
960 CLEAR
970 DISP "COMPUTING TARGET DATA"
980 PRINT
990 ! PRINT "TARGET DATA"
1000 PRINT
1010 OUTPUT 719 ;"P",L9,"Z1K0L3M
     0N601"
1020 WAIT 200
```

```
1030 GOSUB 1890
1040 PRINT " "
1050 PRINT "TRANS. FUNCTION",S$
1060 PRINT " "
1070 ASSIGN# 2 TO C$
1080 FOR M=1 TO M1
1090 N1=B(M,1)-A(M,1)
1100 N2=B(M,2)-A(M,2)
1110 X6=G3(M,1)/(N1^2+N2^2)
1120 X7=G3(M,2)-ATN2(N2,N1)
1130 X7=X7-X9*INT(X7/X9)
1140 IF X7>PI THEN X7=X7-X9
1150 PRINT# 2,M ; X6,X7
1160 ! PRINT USING 970 ; M,X6,X7
1170 IMAGE DD,1X,"X6=",SD.DDDE,1
     X,"X7=",SD.DDDE
1180 NEXT M
1190 ASSIGN# 2 TO *
1200 CLEAR
1210 DISP "CALIBRATION COMPLETED
          ,DATA STORED IN",C$
1220 BEEP @ BEEP @ BEEP
1230 LOCAL 7
1240 END
1250 !
1260 !
1270 !
1280 !
1290 !
1300 !   BACKGROUND DATA
       COLLECTION SUBROUTINE
1310 !
1320 ! OUTPUT 10 TO 15 GHZ AT
          0.1 GHZ STEPS
1330 J=10*(L9-F9) ! FREQ.STARTS
       AT 10 GHZ =100*0.1 GHZ
1340 FOR K=1 TO M1 ! NUMBER OF
            FREQUENCY STEPS
1350 J=J+10*F9
1360 IMAGE 1A,3Z,14A
1370 OUTPUT 719 USING 1360 ; "P"
     ,J,"00Z1K0L3M0N601"
1380 ! 50 MSEC WAIT FOR
       FREQUENCY TO STABILIZE
1390 WAIT 50
1400 ! TAKE DATA IN FROM 722
1410 GOSUB 1550
1420 R1=A1*COS(P1)
1430 I1=A1*SIN(P1)
1440 A(K,1)=R1
1450 A(K,2)=I1
1460 ! PRINT USING 2040 ; A(K,1)
     ,A(K,2)
1470 NEXT K
1480 OUTPUT 719 ;"P",L9,"Z1K0L3M
     0N601"
1490 RETURN
```

```
1500 !
1510 !
1520 !
1530 !
1540 !
1550 ! SUBROUTINE TO ENTER
       MAGNITUDE AND PHASE DATA
       FROM DIGITAL VOLTMETER
1560 !
1570 ! PREPARE DIG. VOLTMETERS
1580 ! TO SEND MAGNITUDE
1590 ! AND PHASE DATA
1600 !
1610 ! N0 READINGS TAKEN AND
       AVERAGED FOR ONE ENTRY
1620 V1=0
1630 F1=0
1640 FOR L=1 TO N0
1650 OUTPUT 720 ;"P0F1R1T1Z1FL0M
     0"
1660 WAIT 10
1670 ENTER 720 ; V
1680 WAIT 10
1690 OUTPUT 722 ;"F1R7T1M3A0H1"
1700 WAIT 10
1710 ENTER 722 ; F
1720 V1=V1+V
1730 F1=F1+F
1740 WAIT 10
1750 NEXT L
1760 V=V1/N0
1770 F=F1/N0
1780 A1=10^V
1790 P1=100*F
1800 P1=DTR(P1)
1810 ! PRINT USING 1810 ; K,A1,P
     1
1820 IMAGE DD,2X,"A=",MD.DDDE,2X
     ,"P=",SD.DDDE
1830 RETURN
1840 !
1850 !
1860 !
1870 !
1880 !
1890 ! TARGET DATA COLLECTION
            SUBROUTINE
1900 !
1910 ! OUTPUT 10 TO 15 GHZ
       AT 0.1 GHZ STEPS
1920 J=10*(L9-F9) ! FREQ.STARTS
       AT 10 GHZ =100*0.1 GHZ
1930 FOR K=1 TO M1 ! NUMBER OF
              FREQUENCY STEPS
1940 J=J+10*F9
1950 IMAGE 1A,3Z,14A
1960 OUTPUT 719 USING 1950 ; "P"
     ,J,"00Z1K0L3M0N601"
```

```
1970 ! 50 MSEC WAIT FOR
1980 ! FREQUENCY TO STABILIZE
1990 ! TAKE DATA IN FROM 722
2000 GOSUB 1550
2010 R1=A1*COS(P1)
2020 I1=A1*SIN(P1)
2030 B(K,1)=R1
2040 B(K,2)=I1
2050 ! PRINT USING 2040 ; B(K,1)
     ,B(K,2)
2060 IMAGE 4X,"R=",SD.DDDE,2X,"I
     =",SD.DDDE
2070 NEXT K
2080 OUTPUT 719 ;"P",L9,"Z1K0L3M
     0N601"
2090 RETURN
2100 !
2110 !
2120 !
2130 !
2140 ! HEADER SUBROUTINE
2150 !
2160 PRINT " "
2170 PRINT " "
2180 CLEAR
2190 DISP "CALIBRATION STANDARD"
     ,S$
2200 DISP "ENTER TGT RNG IN M"
2210 INPUT R$
2220 PRINT "CALIBRATION STANDARD
     ",S$
2230 PRINT "TARGET RANGE",R$
2240 PRINT "********************"
2250 PRINT "********************"
2260 PRINT " "
2270 CLEAR
2280 RETURN
```

C. TARGET PROGRAM

This program computes back scattering cross section and phase of the target signal return, using calibration data obtained in the program "CALIB.DRIVE0" and stored in the file C$. Results are stored in the file G$. Comments and necessary program variable declarations are given at the begining of the main program (lines 10 through 400). Calibration results are then read into computer memory, as well as the background data (lines 410 through 550). If the user wants to take new background data, program calls in background data collection subroutine and the subroutine to enter magnitude and phase data from digital voltmeters. Target is then placed into the anechoic chamber and the target data collection subroutine is called along with subroutine to enter magnitude and phase data from digital voltmeters. Procedures for both background and target data collection are described in the calibration program section in detail. Having calibration, background and target data collected, the main program computes target cross section and phase shift (lines 810 through 930). Cross section and phase shift data could be printed, plotted or both, stored in a newly created or an existing file. New results could be averaged with the measurement results obtained and stored earlier. This procedure allows us to reduce system noise, and can be repeated as many times as we want to (lines 940 through 2100). Header subroutine (lines 2990 through 3190) is written to improve data readability and to provide their documentation.

MAGNITUDE PLOTTING SUBROUTINE and PHASE PLOTTING SUBROUTINE serve to plot target cross section and phase shift respectively, from the results obtained in this program, using HP 7225B plotter (lines 3230 through 4960).

On the other hand, if we want to plot earlier obtained and stored results, "PLOT.DRIVE0" program has to be used. This program is developed using above mentioned plotting subroutines. Target and plotting program are listed bellow.

```
 10 ! "TARGET.DRIVE0"
 20 !
 30 !
 40 ! PROGRAM TO COMPUTE TARGET
 50 ! BACKSCATTERING CROSS
 60 ! SECTION AND PHASE USING
 70 ! C$ DATA AND TO STORE
 80 ! RESULTS IN THE FILE G$.
 90 !
100 !
110 ! FREQUENCIES:10-15 GHZ AT
          0.1 GHZ STEPS
120 !
130 !
140 ! FILE C$ STORES THE SYSTEM
        TRANSFER FUNCTION
150 !
160 ! FILE G$ STORES TARGET DATA
     OBTAINED FROM THIS PROGRAM
170 !
180 ! FILE H$ STORES THEORETICAL
     VALUES FOR PLOTTING OVERLAY
190 !
200 C$="CALIB3.DRIVE1"
210 G$="SCR.DRIVE1"
220 H$="THEOR3.DRIVE1"
230 A$="BKGRND.DRIVE1"
240 ! CREATE G$,52,24
250 ! CREATE A$,51,16
260 !
270 !
280 OPTION BASE 1
290 N0=10 ! DIMENSION OF W()
300 DIM A(51,2)
310 DIM B(51,2) ! TARGET
320 DIM G4(51,2) ! CALIBRATION
330 DIM N(51,3) ! RESULT
340 DIM M9(51,3)
350 N1=51 ! NUMBER OF FREQ.
              CHECKED
360 F9=.1 ! FREQ.STEPS
370 U9=15 ! UPPER FREQ. IN GHZ
380 L9=10 ! LOWER FREQ. IN GHZ
390 DIM T(800,2) ! STORES
       THEORETICAL DATA
400 X9=2*PI
410 ASSIGN# 1 TO C$
420 READ# 1 ; G4(,)
430 ASSIGN# 1 TO *
440 ! MAT PRINT USING 330 ; G4
450 IMAGE 2X,3D.4D
460 REMOTE 7 ! REMOTE ALL
                 DEVICES
470 CLEAR 7 ! CLEAR ALL DEVICES
480 OUTPUT 719 ;"P1Z1K0L3M0N601"
     ! INITIAL SETUP OF 719
490 CLEAR
```

```
500 DISP "DO YOU WANT TO USE THE
      MOST RECENT BACKGROUND
         DATA?    Y/N"
510 INPUT P$
520 IF P$="N" THEN 570
530 ASSIGN# 4 TO A$
540 READ# 4 ; A(,)
550 ASSIGN# 4 TO *
560 GOTO 700
570 DISP "REMOVE TGT FROM CHAMBE
    R PUSH 'CONT' WHEN READY"
580 LOCAL 7
590 BEEP @ BEEP
600 PAUSE
610 DISP "TAKING BKGRND DATA"
620 REMOTE 7
630 OUTPUT 719 ;"P",L9,"Z1K0L3M0
    N601" ! INITIAL SETUP OF 719
640 WAIT 100
650 GOSUB 2160
660 ASSIGN# 5 TO A$
670 PRINT# 5 ; A(,)
680 ASSIGN# 5 TO *
690 CLEAR
700 DISP "PUT TARGET INTO CHAMBE
    R,PUSH 'CONT' WHEN READY"
710 LOCAL 7
720 BEEP @ BEEP
730 PAUSE
740 REMOTE 7
750 OUTPUT 719 ;"P",L9,"Z1K0L3M0
    N601" ! INITIAL SETUP OF 719
760 WAIT 500
770 GOSUB 3030
780 CLEAR
790 DISP "COMPUTING TARGET DATA"
800 GOSUB 2730
810 F0=L9-F9
820 FOR M=1 TO N1
830 F0=F0+F9
840 N(M,1)=F0
850 X7=B(M,1)-A(M,1)
860 X8=B(M,2)-A(M,2)
870 X6=(X7^2+X8^2)*G4(M,1)
880 N(M,2)=X6
890 X8=ATN2(X8,X7)+G4(M,2)
900 X8=X8-X9*INT(X8/X9)
910 IF X8>PI THEN X8=X8-X9
920 N(M,3)=X8
930 NEXT M
940 DISP "PRINT DATA? Y/N"
950 BEEP @ BEEP
960 INPUT P$
970 IF P$="N" THEN 1010
980 PRINT "     FREQ      CRSEC
       PHASE"
990 MAT PRINT USING 1000 ; N
```

```
1000 IMAGE 2X,3D.4D
1010 CLEAR
1020 LOCAL 7
1030 DISP "PLOT MAGNITUDE FOR
          THIS MEASURMENT? Y/N"
1040 INPUT P$
1050 IF P$="N" THEN 1090
1060 DISP "SELECT PEN. PUSH
          'CONT' WHEN READY"
1070 PAUSE
1080 GOSUB 3230
1090 CLEAR
1100 DISP "PLOT PHASE FOR THIS
          MEASURMENT ? Y/N"
1110 BEEP @ BEEP
1120 INPUT P$
1130 IF P$="N" THEN 1170
1140 DISP "SELECT PEN. PUSH
          'CONT' WHEN READY"
1150 PAUSE
1160 GOSUB 4340
1170 CLEAR
1180 DISP "DO YOU WANT TO MAKE
     AVER. WITH PREVIOUS DATA?"
1190 DISP "?Y/N"
1200 BEEP @ BEEP
1210 INPUT P$
1220 IF P$="Y" THEN 1420
1230 DISP "DO YOU WANT TO STORE
          DATA ? Y/N "
1240 INPUT P$
1250 IF P$="N" THEN 1880
1260 M0=1
1270 DISP "DO YOU WANT TO STORE
          DATA IN FILE"
1280 DISP G$
1290 DISP "? Y/N"
1300 INPUT P$
1310 IF P$="Y" THEN 1380
1320 DISP "ENTER NAME OF THE DAT
     A FILE TO BE USED FOR STORA
     GE"
1330 INPUT G$
1340 DISP "IS THIS AN OLD FILE
       TO BE UPDATED ? Y/N "
1350 INPUT P$
1360 IF P$="Y" THEN 1380
1370 CREATE G$,52,24
1380 ASSIGN# 2 TO G$
1390 PRINT# 2 ; M0,N(,)
1400 ASSIGN# 2 TO *
1410 GOTO 1880
1420 DISP "ARE THE DATA STORED
                  IN FILE"
1430 DISP G$
1440 DISP "? Y/N"
1450 INPUT P$
```

```
1460 IF P$="Y" THEN 1490
1470 DISP "ENTER NAME OF DATA
          FILE TO BE USED FOR
              THE AVERAGE"
1480 INPUT G$
1490 ASSIGN# 6 TO G$
1500 READ# 6 ; M0,M9(,)
1510 ASSIGN# 6 TO *
1520 FOR K=1 TO N1
1530 M9(K,2)=M9(K,2)*M0+N(K,2)
1540 M9(K,2)=M9(K,2)/(M0+1)
1550 M9(K,3)=M9(K,3)*M0+N(K,3)
1560 M9(K,3)=M9(K,3)/(M0+1)
1570 N(K,2)=M9(K,2)
1580 N(K,3)=M9(K,3)
1590 NEXT K
1600 M0=M0+1
1610 ASSIGN# 7 TO G$
1620 PRINT# 7 ; M0,N(,)
1630 ASSIGN# 7 TO *
1640 PRINT "DATA IS AVERAGE OF",
     M0,"MEASURMENTS"
1650 DISP "PRINT DATA? Y/N"
1660 BEEP @ BEEP
1670 INPUT P$
1680 IF P$="N" THEN 1720
1690 PRINT "     FREQ       CRSEC
        PHASE"
1700 MAT PRINT USING 1000 ; N
1710 IMAGE 2X,3D.4D
1720 DISP "PLOT MAGNITUDE?  Y/N"
1730 BEEP @ BEEP
1740 INPUT P$
1750 IF P$="N" THEN 1790
1760 DISP "SELECT PEN FOR MAGNIT
     UDE PLOT. PUSH 'CONT' WHEN
     READY."
1770 PAUSE
1780 GOSUB 3230
1790 CLEAR
1800 DISP "PLOT PHASE?  Y/N"
1810 BEEP @ BEEP
1820 INPUT P$
1830 IF P$="N" THEN 1870
1840 DISP "SELECT PEN AND CHANGE
        PAPER FOR PHASE  PLOT.
        PUSH 'CONT' WHEN READY."
1850 PAUSE
1860 GOSUB 4340
1870 CLEAR
1880 DISP "DO YOU WANT TO"
1890 DISP "OBTAIN DATA"
1900 DISP "FOR A NEW TARGET?"
1910 DISP " "
1920 DISP "ENTER Y/N"
1930 INPUT P$
1940 IF P$="N" THEN 2070
```

```
1950 DISP "DO YOU WANT TO USE
      THE SAME FILE"
1960 DISP G$
1970 DISP "TO STORE NEW DATA?
                  Y/N"
1980 INPUT P$
1990 IF P$="Y" THEN 2060
2000 DISP "ENTER NEW FILE NAME
       TO STORE TARGET DATA"
2010 INPUT G$
2020 DISP "IS THIS AN OLD FILE
        TO BE UPDATED? Y/N"
2030 INPUT P$
2040 IF P$="Y" THEN 2060
2050 CREATE G$,53,24
2060 GOTO 460
2070 CLEAR
2080 DISP "END OF PROGRAM"
2090 BEEP @ BEEP @ BEEP
2100 END
2110 !
2120 !
2130 !
2140 !
2150 !     BACKGROUND DATA
2160 ! COLLECTION SUBROUTINE
2170 !
2180 ! OUTPUT 10 TO 15 GHZ
2190 J=10*(L9-F9) ! FREQ. STARTS
          AT 10 GHZ TO BE INCREM.
            AT 0.1 GHZ STEPS

2200 FOR K=1 TO N1 ! NUMBER OF
           FREQUENCY STEPS

2210 J=J+10*F9
2220 IMAGE 1A,3Z,14A
2230 OUTPUT 719 USING 2220 ; "P"
     ,J,"00Z1K0L3M0N601"
2240 ! 50 MSEC WAIT FOR
        FREQUENCY TO STABILIZE
2250 WAIT 50
2260 ! TAKE DATA IN FROM 722
2270 GOSUB 2420
2280 R1=A1*COS(P1)
2290 I1=A1*SIN(P1)
2300 A(K,1)=R1
2310 A(K,2)=I1
2320 ! PRINT "I1=",A(K,2)
2330 ! PRINT "R1=",A(K,1)
2340 NEXT K
2350 OUTPUT 719 ;"P",L9,"Z1K0L3M
     0N601" ! INIT. SETUP OF 719
2360 RETURN
2370 !
2380 !
2390 !
```

```
2400 !
2410 !
2420 ! SUBROUTINE TO ENTER MAGNI
     TUDE AND PHASE DATA FROM
        DIGITAL VOLTMETERS
2430 !
2440 ! PREPARE DIGIT.VOLTMETERS
          TO SEND DATA
2450 ! N0 READINGS TAKEN AND
     AVERAGED FOR ONE ENTRY
2460 V1=0
2470 W1=0
2480 FOR L=1 TO N0
2490 OUTPUT 720 ;"F1R1T1Z1FL0M0"
2500 WAIT 10
2510 ENTER 720 ; V0
2520 WAIT 10
2530 OUTPUT 722 ;"F1R7T1M3A0H1"
2540 WAIT 10
2550 ENTER 722 ; W0
2560 V1=V1+V0
2570 W1=W1+W0
2580 WAIT 10
2590 NEXT L
2600 V0=V1/N0
2610 W0=W1/N0
2620 A1=10^V0
2630 P1=100*W0
2640 ! PRINT "A1=",A1
2650 P1=DTR(P1)
2660 ! PRINT "P1=",P1
2670 RETURN
2680 !
2690 !
2700 !
2710 !
2720 !      TARGET DATA
2730 ! COLLECTION SUBROUTINE
2740 !
2750 !
2760 ! OUTPUT 10 TO 15 GHZ AT
          0.1 GHZ STEPS
2770 J=10*(L9-F9) ! INITIAL FREQ
     UENCY AT 10 GHZ=100*0.1 GHZ
2780 FOR K=1 TO N1 ! FREQ.STEPS
2790 J=J+10*F9 ! .1 GHZ INCREM.
2800 IMAGE 1A,3Z,14A
2810 OUTPUT 719 USING 2800 ; "P"
     ,J,"00Z1K0L3M0N601"
2820 ! 50 MSEC WAIT FOR
       FREQUENCY TO STABILIZE
2830 WAIT 50
2840 ! TAKE DATA IN FROM 722
2850 GOSUB 2420
2860 R1=A1*COS(P1)
2870 I1=A1*SIN(P1)
2880 B(K,1)=R1
```

```
2890 B(K,2)=I1
2900 ! PRINT "R1=",B(K,1)
2910 ! PRINT "I1=",B(K,2)
2920 NEXT K
2930 OUTPUT 719 ;"P",L9,"Z1K0L3M
     0N601" ! INIT. SETUP OF 719
2940 RETURN
2950 !
2960 !
2970 !
2980 !
2990 ! HEADER SUBROUTINE
3000 !
3010 !
3020 D$="MONTH/DATE/YEAR"
3030 PRINT " "
3040 PRINT " "
3050 CLEAR
3060 DISP "ENTER TODAY'S DATE -
     MONTH,DATE,YEAR"
3070 INPUT D$
3080 DISP "ENTER TGT DESCRIPTION
     "
3090 INPUT T$
3100 DISP "ENTER TGT RANGE"
3110 INPUT R$
3120 PRINT D$
3130 PRINT "TARGET IS ",T$
3140 PRINT "TGT RANGE",R$
3150 PRINT "**********"
3160 PRINT "**********"
3170 PRINT " "
3180 CLEAR
3190 RETURN
3200 !
3210 !
3220 !
3230 ! MAGNITUDE PLOTTING
3240 !    SUBROUTINE
3250 !
3260 !
3270 PLOTTER IS 705
3280 LOCATE 32,122,20,85
3290 FRAME
3300 ! SEARCH FOR MAX  & MIN.
3310 ! S0=N(1,2)
3320 ! S1=S0
3330 ! FOR M=2 TO N1
3340 ! IF S0>N(M,2) THEN S0=N(M,
     2)
3350 ! IF S1<N(M,2) THEN S1=N(M,
     2)
3360 ! NEXT M
3370 DISP "ENTER LOWER VALUE FOR
          MAGNITUDE PLOTTING"
3380 BEEP @ BEEP
3390 INPUT S0
```

```
3400 DISP "ENTER UPPER VALUE FOR
        MAGNITUDE PLOTTING"
3410 INPUT S1
3420 L1=INT(L9)
3430 U1=CEIL(U9)
3440 S3=LGT(S1)
3450 S4=INT(S3)-1
3460 S5=S3-S4
3470 S5=INT(10^S5)+1
3480 S4=10^S4
3490 L0=INT(S0/S4)
3500 IF S5-L0<=14 THEN 3580
3510 IF S5-L0>=50 THEN 3550
3520 S5=.5*S5
3530 S4=S4*2
3540 GOTO 3490
3550 S5=.2*S5
3560 S4=5*S4
3570 GOTO 3490
3580 L0=S4*L0
3590 U0=S5*S4
3600 D0=U0-L0
3610 SCALE L1,U1,L0,U0
3620 FXD 0,4
3630 LAXES -1,S4,L1,L0
3640 MOVE L1,0
3650 FOR K=1 TO N1
3660 M9=N(K,1)
3670 R9=N(K,2)
3680 MOVE M9,R9
3690 DRAW M9,R9
3700 ! GOSUB 4060
3710 NEXT K
3720 M5=(U1+L1)/2
3730 MOVE M5,L0-.09*D0
3740 LORG 5 @ CSIZE 3,1,0
3750 ! LABEL "FREQUENCY (GHz)"
3760 MOVE M5,L0-.16*D0
3770 ! LABEL "Fig. . .  TARGET2
     - Cross Section"
3780 MOVE L1-.7,.5*(L0+U0)
3790 LDIR PI/2
3800 ! LABEL "CROSS SECTION (SQ.
     METERS)"
3810 MOVE M5,U0+.095*D0
3820 LDIR 0
3830 CSIZE 3,1,0
3840 ! LABEL "TARGET: SPHERE D=1
     .125 inch."
3850 MOVE M5,U0+.06*D0
3860 ! LABEL "POLARIZATION: HORI
     ZONTAL"
3870 MOVE M5,U0+.025*D0
3880 ! LABEL "MATERIAL: ALUMINUM
     "
3890 PENUP
```

```
3900 DISP "OVERLAY THEORETICAL
          CURVE? Y/N"
3910 !
3920 INPUT P$
3930 IF P$="N" THEN 4190
3940 DISP "IS THE THEORETICAL
     DATA STORED IN THE FILE",H$
3950 DISP "?  Y/N"
3960 INPUT P$
3970 IF P$="Y" THEN 4000
3980 DISP "ENTER NAME OF THE
     DATA FILE TO BE PLOTTED."
3990 INPUT H$
4000 BEEP @ BEEP
4010 DISP "CHANGE PEN IF DESIRED
     . PUSH 'CONT' WHEN READY."
4020 PAUSE
4030 ASSIGN# 3 TO H$
4040 J1=(L9-2)*50
4050 J2=(U9-2)*50
4060 FOR J=J1 TO J2
4070 READ# 3,J ; T(J,1),T(J,2)
4080 NEXT J
4090 ASSIGN# 3 TO *
4100 F0=L9
4110 R9=T(J1,1)
4120 MOVE F0,R9
4130 FOR I=J1 TO J2
4140 F0=F0+.02
4150 R9=T(I,1)
4160 DRAW F0,R9
4170 NEXT I
4180 PENUP
4190 RETURN
4200 !
4210 !
4220 !
4230 ! PLOT CROSS
4240 MOVE M9,R9
4250 CSIZE 2,.5,0
4260 LABEL "+"
4270 ! IMOVE .00025,.00025
4280 ! IDRAW -.0005,0
4290 RETURN
4300 !
4310 !
4320 !
4330 !
4340 ! PHASE PLOTTING SUBROUTINE
4350 !
4360 PLOTTER IS 705
4370 LOCATE 32,122,20,85
4380 FRAME
4390 S4=.5
4400 U0=1
4410 L0=-1
4420 D0=U0-L0
```

```
4430 SCALE L1,U1,L0,U0
4440 FXD 0,3
4450 LAXES -1,S4,L1,L0
4460 MOVE L1,0
4470 FOR K=1 TO N1
4480 M9=N(K,1)
4490 R9=N(K,3)/PI
4500 MOVE M9,R9
4510 DRAW M9,R9
4520 ! GOSUB 4680
4530 NEXT K
4540 MOVE M5,L0-.09*D0
4550 LORG 5 @ CSIZE 3,1,0
4560 ! LABEL "FREQUENCY (GHz)"
4570 MOVE M5,L0-.16*D0
4580 ! LABEL "Fig. . .  TARGET2
     - Phase"
4590 MOVE L1-.7,.5*(L0+U0)
4600 LDIR PI/2
4610 LABEL "PHASE (PI)"
4620 MOVE M5,U0+.095*D0
4630 LDIR 0
4640 CSIZE 3,1,0
4650 ! LABEL "TARGET: SPHERE D=1
     .125 inch."
4660 MOVE M5,U0+ 06*D0
4670 ! LABEL "POLARIZATION: HORI
     ZONTAL"
4680 MOVE M5,U0+.025*D0
4690 ! LABEL "MATERIAL: ALUMINUM
     "
4700 PENUP
4710 DISP "OVERLAY THEORETICAL
           CURVE? Y/N"
4720 INPUT P$
4730 IF P$="N" THEN 4860
4740 BEEP @ BEEP
4750 DISP "CHANGE PEN IF DESIRED
     . PUSH 'CONT' WHEN READY."
4760 PAUSE
4770 F0=L9
4780 R9=T(J1,2)/PI
4790 MOVE F0,R9
4800 FOR I=J1 TO J2
4810 F0=F0+.02
4820 R9=T(I,2)/PI
4830 DRAW F0,R9
4840 NEXT I
4850 PENUP
4860 RETURN
4870 !
4880 !
4890 !
4900 ! PLOT DOT
4910 MOVE M9,R9
4920 CSIZE 2,.5,0
```

```
4930 LABEL "*"
4940 ! IMOVE .00025,.00025
4950 ! IDRAW -.0005,0
4960 RETURN
```

```
 10 ! "PLOT.DRIVE0"
 20 !
 30 ! PROGRAM TO PLOT
 40 ! BACKSCATTERING CROSS
 50 ! SECTION AND PHASE VS.
 60 ! FREQUENCY USING
 70 ! STORED DATA.
 80 !
 90 G$="SCR4.DRIVE1"
100 H$="THEOR0.DRIVE1"
110 OPTION BASE 1
120 DIM N(51,3) ! DATA TO BE
      PLOTTED
130 N1=51 ! NUMBER OF
      FREQUENCES CHECKED.
140 F9=.1 ! FREQ.STEPS
150 U9=15 ! UPPER FREQ. IN GHZ
160 L9=10 ! LOWER FREQ. IN GHZ
170 DIM T(800,2) ! STORES
            THEORETICAL DATA
180 CLEAR
190 DISP "DO YOU WANT TO PLOT"
200 DISP "FROM THE FILE:"
210 DISP G$
220 DISP "ENTER Y/N?"
230 INPUT P$
240 IF P$="Y" THEN 290
250 DISP "ENTER NAME OF FILE "
260 DISP "TO BE PLOTTED"
270 BEEP @ BEEP
280 INPUT G$
290 ASSIGN# 1 TO G$
300 READ# 1 ; M0,N(,)
310 ASSIGN# 1 TO *
320 X9=2*PI
330 DISP "PRINT DATA? Y/N"
340 BEEP @ BEEP
350 INPUT P$
360 IF P$="N" THEN 400
370 PRINT "     FREQ       CRSEC
      PHASE"
380 MAT PRINT USING 390 ; N
390 IMAGE 2X,3D.4D
400 CLEAR
410 DISP "PLOT MAGNITUDE?  Y/N"
420 BEEP @ BEEP
430 INPUT P$
440 IF P$="N" THEN 480
450 DISP "SELECT PEN FOR MAGNITU
    DE PLOT. PUSH 'CONT' WHEN RE
    ADY."
460 PAUSE
470 GOSUB 740
480 CLEAR
490 DISP "PLOT PHASE?  Y/N"
500 BEEP @ BEEP
510 INPUT P$
```

```
520 IF P$="N" THEN 560
530 DISP "SELECT PEN AND CHANGE
    PAPER FOR PHASE  PLOT. PUSH
    'CONT' WHEN READY."
540 PAUSE
550 GOSUB 1800
560 CLEAR
570 DISP "DO YOU WANT TO"
580 DISP "PLOT DATA"
590 DISP "FORM ANOTHER FILE?"
600 DISP " "
610 DISP "ENTER Y/N"
620 INPUT P$
630 IF P$="Y" THEN 110
640 CLEAR
650 DISP "END OF PROGRAM"
660 BEEP @ BEEP @ BEEP
670 END
680 !
690 !
700 !
710 !
720 !
730 !
740 ! MAGNITUDE PLOTTING
750 ! SUBROUTINE
760 !
770 PLOTTER IS 705
780 LOCATE 32,122,20,85
790 FRAME
800 ! SEARCH FOR MAX. & MIN.
810 ! S0=N(1,2)
820 ! S1=S0
830 ! FOR M=2 TO N1
840 ! IF S0>N(M,2) THEN S0=N(M,2
    )
850 ! IF S1<N(M,2) THEN S1=N(M,2
    )
860 ! NEXT M
870 DISP "ENTER LOWER VALUE FOR
        MAGNITUDE PLOTTING"
880 BEEP @ BEEP
890 INPUT S0
900 DISP "ENTER UPPER VALUE FOR
        MAGNITUDE PLOTTING"
910 INPUT S1
920 L1=INT(L9)
930 U1=CEIL(U9)
940 S3=LGT(S1)
950 S4=INT(S3)-1
960 S5=S3-S4
970 S5=INT(10^S5)+1
980 S4=10^S4
990 L0=INT(S0/S4)
1000 IF S5-L0<=14 THEN 1080
1010 IF S5-L0>=50 THEN 1050
1020 S5=.5*S5
```

```
1030 S4=S4*2
1040 GOTO 990
1050 S5=.2*S5
1060 S4=5*S4
1070 GOTO 990
1080 L0=S4*L0
1090 U0=S5*S4
1100 D0=U0-L0
1110 SCALE L1,U1,L0,U0
1120 FXD 0,4
1130 LAXES -1,S4,L1,L0
1140 MOVE L1,0
1150 FOR K=1 TO N1
1160 M9=N(K,1)
1170 R9=N(K,2)
1180 MOVE M9,R9
1190 DRAW M9,R9
1200 NEXT K
1210 M5=(U1+L1)/2
1220 MOVE M5,L0-.09*D0
1230 LORG 5 @ CSIZE 3,1,0
1240 LABEL "FREQUENCY (GHz)"
1250 MOVE M5,L0-.16*D0
1260 LABEL "Fig.3.13.  TARGET3 -
      CROSS SECTION"
1270 MOVE L1-.7,.5*(L0+U0)
1280 LDIR PI/2
1290 LABEL "CROSS SECTION (SQ.ME
     TERS)"
1300 MOVE M5,U0+.08*D0
1310 LDIR 0
1320 CSIZE 3,1,0
1330 LABEL "TARGET: SPHERE (D=3.
     187in./ALUMINUM)"
1340 MOVE M5,U0+.03*D0
1350 LABEL "POLARIZATION: HORIZO
     NTAL"
1360 PENUP
1370 DISP "OVERLAY THEORETICAL
                CURVE? Y/N"
1380 !
1390 INPUT P$
1400 IF P$="N" THEN 1660
1410 DISP "IS THE THEORETICAL
     DATA STORED IN THE FILE",H$
1420 DISP "?  Y/N"
1430 INPUT P$
1440 IF P$="Y" THEN 1470
1450 DISP "ENTER NAME OF THE
     DATA FILE TO BE PLOTTED."
1460 INPUT H$
1470 BEEP @ BEEP
1480 DISP "CHANGE PEN IF DESIRED
     . PUSH 'CONT' WHEN READY."
1490 PAUSE
1500 ASSIGN# 3 TO H$
1510 J1=(L9-2)*50
```

```
1520 J2=(U9-2)*50
1530 FOR J=J1 TO J2
1540 READ# 3,J ; T(J,1),T(J,2)
1550 NEXT J
1560 ASSIGN# 3 TO *
1570 F0=L9
1580 R9=T(J1,1)
1590 MOVE F0,R9
1600 FOR I=J1+1 TO J2
1610 F0=F0+.02
1620 R9=T(I,1)
1630 DRAW F0,R9
1640 NEXT I
1650 PENUP
1660 RETURN
1670 !
1680 !
1690 !
1700 ! PLOT CROSS
1710 MOVE M9,R9
1720 CSIZE 2, 5,0
1730 LABEL "+"
1740 ! IMOVE .00025,.00025
1750 ! IDRAW -.0005,0
1760 RETURN
1770 !
1780 !
1790 !
1800 ! PHASE PLOTTING SUBROUTINE
1810 !
1820 PLOTTER IS 705
1830 LOCATE 32,122,20,85
1840 FRAME
1850 S4=.5
1860 L1=INT(L9)
1870 U1=CEIL(U9)
1880 U0=1
1890 L0=-1
1900 D0=U0-L0
1910 M5=(U1+L1)/2
1920 SCALE L1,U1,L0,U0
1930 FXD 0,2
1940 LAXES -1,S4,L1,L0
1950 MOVE L1,0
1960 FOR K=1 TO N1
1970 M9=N(K,1)
1980 R9=N(K,3)/PI
1990 MOVE M9,R9
2000 DRAW M9,R9
2010 NEXT K
2020 MOVE M5,L0-.09*D0
2030 LORG 5 @ CSIZE 3,1,0
2040 LABEL "FREQUENCY (GHz)"
2050 MOVE M5,L0-.16*D0
2060 LABEL "Fig.3.14.  TARGET3 -
      PHASE"
2070 MOVE L1-.7,.5*(L0+U0)
```

```
2080 LDIR PI/2
2090 LABEL "PHASE (PI)"
2100 MOVE M5,U0+.08*D0
2110 LDIR 0
2120 CSIZE 3,1,0
2130 LABEL "TARGET: SPHERE (D=3.
     187in./ALUMINUM)"
2140 MOVE M5,U0+.03*D0
2150 LABEL "POLARIZATION: HORIZO
     NTAL"
2160 PENUP
2170 DISP "OVERLAY THEORETICAL C
     URVE? Y/N"
2180 INPUT P$
2190 IF P$="N" THEN 2320
2200 BEEP @ BEEP
2210 DISP "CHANGE PEN IF DESIRED
     . PUSH 'CONT' WHEN READY."
2220 PAUSE
2230 F0=L9
2240 R9=T(J1,2)/PI
2250 MOVE F0,R9
2260 FOR I=J1+1 TO J2
2270 F0=F0+.02
2280 R9=T(I,2)/PI
2290 DRAW F0,R9
2300 NEXT I
2310 PENUP
2320 RETURN
2330 !
2340 !
2350 !
2360 ! PLOT DOT
2370 MOVE M9,R9
2380 CSIZE 2,.5,0
2390 LABEL "*"
2400 ! IMOVE .00025,.00025
2410 ! IDRAW -.0005,0
2420 RETURN
```

V. SUMMARY AND CONCLUSIONS

Demands on target cross section measurements and analysis have increased considerably in recent years. There are several reasons for this:

- Great attention has been paid to cross section reduction through the applications of radio frequency absorbing materials. Returns from many targets of practical interest are suppressed.
- Introduction of nonmetallic materials into target construction has further complicated target scattering properties.
- Sophisticated radar systems, on the other hand, provided additional means for target discrimination. For example, the polarization characteristics of a target can be acquired and utilized.

In this work the calibration of the CW scattering range was performed. The theoretical solution had been tested against experimental results for several perfectly conducting spheres of different diameters. Back scattered fields were measured for three spheres and five finite length, thin walled, right circular cylinders. Corresponding back scattering cross sections and return phase shifts were obtained. Differences between theory and experiment were discussed in terms of noises introduced by such sources as background reflections, system noise, target-antenna distance ,and target support problems. Agreement between theory and measurement data was good if the calibration and target data acquisition were performed in a short time interval. Otherwise, as the time elapses, differences between theoretical and measurement data became

more and more pronounced. This problem requires further study.

Measurements on the cylinders showed that for broad side incidence, the number and location of the resonance frequencies are strongly dependent on the diameter of the cylinder. The back scattering cross section depends on both the cylinder diameter and its length. The phase shift, on the other hand, depends only on the cylinder diameter. A change in polarization provides additional cross section and phase data. Several cylinders (targets) might be distinguished by comparing acquired data of their phases and cross sections for two orthogonal polarizations. Future works will investigate applicability and reliability of this approach towad the identification of targets of complex shapes.

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